"BREAKTHROUGH" TECHNOLOGIES

DEVELOPED BY THE AIR FORCE RESEARCH

LABORATORY AND ITS PREDECESSORS

December 21, 2005

Air Force Research Laboratory History Program

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AIR FORCE RESEARCH LABORATORY (AFRL) "BREAKTHROUGH" TECHNOLOGIES

PREFACE

This history narrates the development of "breakthrough" technologies by the Air Force Research Laboratory and its predecessor organizations. Encouraged by AFRL's Executive Director, Mr. Lester Mc Fawn, AFRL's history program researched and wrote nearly fifty scholarly essays. These extend over the full gamut of Air Force technology activities. The essays elucidate, in a brief and informative manner, the development of much "cutting-edge" technology generated over the years by the United States Air Force and installed into the Air Force's operational forces. Without these technologies, today's Air Force would not be the most powerful and effective in the history of this planet.

Eight members of the AFRL history program contributed to the writing, editing, and production of this history. These include: Dr. James Aldridge, Ms. Shari Christy, Dr. Robert Duffner, Dr. Joseph Marchese, Dr. Barron Oder, Mr. Kevin Rusnak, Dr. Robert White, and Dr. Craig Waff—who departed midway through the project. Additionally, because of constraints of time and personnel, the Munitions Directorate (MN) contributed four essays on their technology directorate's "breakthrough" efforts. Authors are identified in the MN essays.

Mr. McFawn has decided to continue this project. By the conclusion of 2006 the AFRL history program will have produced a second volume, which will narrate the development of approximately fifty more "breakthrough" technologies developed by AFRL and its predecessor organizations. During 2007 the AFRL history program will embark upon a third phase of the project, producing a volume that focuses upon several key Air Force operational systems--detailing the contributions of AFRL and its predecessor organizations to these systems.

Like this volume, both new volumes will be distributed to high levels of federal, DOD and AF leadership.

The AFRL history program thanks all those who supplied documents, reviewed drafts, and explained complex technical matters to the historians. This help was unseen but crucial.

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JOSEPH MARCHESE, PhD
Lead Historian, AFRL

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AIR FORCE RESEARCH LABORATORY
BREAKTHROUGH TECHNOLOGIES
(Sorted Alphabetically)

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Accelerometer-Based Penetration Fuzing[1]

Penetrating weapons requiring detonation after impact have historically utilized pyrotechnic or electronic delays. Early exceptions were fuzes that employed a mechanical void sensing mechanism whereby the fuze function would occur when the first void was reached or the weapon came to rest, e.g. the Paverock of the late 1960s. Studies in the mid 1970s revealed that maximum runway damage occurred at a specific depth of burial, independent of runway thickness, indicating that depth of burial was the optimum parameter for the fuzing function. In the mid 1970s the Air Force began designing and fabricating their own instrumentation and extended the capability to include monitoring fuze function during target penetration. Weaponization of this capability began in the 1980s with contracted fuze development programs.[2]

During this time period, there was a proliferation of hardened targets world-wide. These varied from simple structures such as aircraft shelters and buildings to complex heavily hardened and deeply buried command, control and communication facilities. The target set also included fabrication and storage facilities for weapons of mass destruction (WMD) (i.e. nuclear, biological and chemical) demanding burst point control and low collateral damage. Hard target penetrators were developed to attack these targets. Fielded hard target weapons used fuzes employing fixed time delays after impact to effectively utilize

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[1] The following article was researched and written by Mr. Steven L. Smith, Mr. Jefferson K. Oliver, and Mr. Richard Mabry, all from the Fuzes Branch of the Ordnance Division of AFRL's Munitions Directorate (AFRL/MNMF).

[2] The history of fuzes in the first four paragraphs is taken from: E-mail, Steven L. Smith, AFRL/MNMF, to Kevin M. Rusnak, AFRL/HO, "FW: History Papers Followup," 19 Jan 06, w/attachment, unpublished paper, Steven L. Smith, AFRL/MNMF, Richard Mabry, AFRL/MNMF, and Jefferson K. Oliver, AFRL/MNMF, "Accelerometer-Based Penetration Fuzes," n.d.

time delay fuzing schemes (fixed or multiple setting), perfect structural knowledge of the target needed to be known, and impact conditions that had to be accurately predicted. The variability of these conditions proved to be difficult to predict even for controlled penetration sled tests. Available intelligence data was limited for hard targets. Specific target parameters such as precise depth, layer thickness (i.e. roof, floor thickness) or hardness were often unknown.

Uncertainty in time of penetration increased with depth causing fuzing error to increase when attacking deeper targets. Multiple weapons drops against an underground target, with varying fuze delay times in an attempt to get one to detonate at the right location within the target structure, proved inefficient and often ineffective. This problem with time delay error pointed to the need for a fuze with void-sensing capability. If the void(s) within the target structure can be sensed, then a better fuzing decision can be made. Normally the desired location for initiation of the warhead was within the void of a buried target to cause maximum damage. If warhead detonation within the void were to be achieved then the target was defeated more effectively and efficiently than by using time delay after initial target impact.

In response to the growing threat, emphasis in penetration fuze development shifted from airfield attack to defeat of hardened and buried targets. Exploratory and advanced developments were conducted on a fuzing system for the Hard Target Weapon (HTW). This system contained an accelerometer and a remotely programmable microcontroller to provide real time decision capability during target penetration.

In the first Gulf War it became clear that a void-sensing "smart fuze" was required for the Bomb Live Unit (BLU)-113 warhead application. The fielding of the BLU-113 and its use against high value hardened deeply buried targets could not be effective with a time delay fuze because of the errors caused by variability of the structural makeup of the targets and weapon impact conditions. The HTW

fuze program was redirected to support the GBU-28 (BLU-113 warhead). The program was accelerated to meet an Advanced Concept Technology Demonstration schedule. Several successful sled and flight tests were conducted demonstrating the potential of an accelerometer-based smart fuze to defeat hard and deeply buried targets.[3]

Munitions such as the BLU-109 (GBU-24, GBU-27, GBU-31) and BLU-113 (GBU-28) had a limited potential against a broad range of hard targets because of deficiencies in inventory fuzes; that is, the fixed time delays for current fuzes limited the optimum damage potential to a narrow set of delivery conditions and target types. The Hard Target Smart Fuze (HTSF) was designed for these applications and was adapted for Miniature Munitions Technology (predecessor to the Small Diameter Bomb) and Advanced Unitary Penetrator (AUP) applications.[4]

The HTSF program developed and demonstrated the first accelerometer-based fuze for penetrating munitions. The HTSF demonstrated the ability of electronics to survive typical penetration shock environments and the ability to determine the general location of the penetrator within the target and make a burst point decision based on a preprogrammed algorithm. The fuze design was capable of distinguishing between concrete, soil, and air during the penetration event, which provided the ability to detonate the warhead at any desired location within the target. This capability increased the effectiveness of current and future hard target penetrating munitions which employed a standard 3-inch fuze well, charging well, and internal plumbing. The HTSF also offered mission versatility via the potential to program the fuze with a Ground Setter Unit prior to the mission or from the cockpit through a MIL-STD 1760/1553 interface while in

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[3]   Public Release Contract Award Announcement, n.a., "Hard Target Smart Fuze (HTSF)," Aug 1998.

[4]   *Ibid.*

flight. Although the HTSF entered engineering development, the program was canceled mainly due to the excessive cost of the fuze.[5]

The Multiple Event Hard Target Fuze (MEHTF) program was initiated to address anticipated fuzing needs for future penetrating weapons. Specific technology limitations were identified and the program was structured to address these limitations. These limitations included: (1) Reduced fuze size to facilitate use in small penetrators. (2) Low fuze cost to be competitive with time delay fuzing. (3) Accurate target media detection capability for detection of thin hard layers and to allow quick detection of voids. (4) A multiple event capability for complex multiple function warheads. (5) Survivability in more severe shock environments.[6]

Fuzes that survived high impact conditions and accurately detected location within the target increased the ability of penetrating munitions to defeat underground bunkers. The MEHTF provided an accurate and low cost solution to fuzing for hard target defeat. The MEHTF was the first low cost all-electronic penetration fuze with the ability to survive a rigid body deceleration shock level as high as 30,000 g_c (measured deceleration filtered at 2,000 Hz). The ability to detect thin (4 inch) concrete layers and quickly detect voids within a target was demonstrated in Miniature Munitions Technology (MMT) dynamic penetration tests. Control of multiple fuzes for multiple warhead events was also demonstrated through static testing. The MEHTF technology transitioned to Survivable Thermostable Robust Intelligent FuzE (STRIFE), and to the United

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[5]   *Ibid.*

[6]   Article, n.a., "Flexible Survivable Non-Volatile Data Recorder," *Air Force Research Laboratory Technology Horizons*, Dec 00; Success story, n.a. [AFRL/MN], "Low-Cost All-Electronic Penetration Fuze Exceeds Penetration Testing Objectives," Mar 03.

Kingdom's Precision Guided Bomb (PGB) program where it is being further developed as the fuze for PGB.[7]

The STRIFE program developed a hard target, intelligent fuze with a low energy firing system to survive high speed impact into realistic targets containing rock and/or reinforced concrete. The STRIFE fuze integrated with a High Speed Penetrator (HSP), detonates the explosive payload at the correct point inside the target based on programmed time, void, layer, or depth, and incorporates back-up firing modes. The HSP is one of the primary munitions deployed by the Common Aero Vehicle (CAV).[8]

The STRIFE point-of-departure packaging design was the MEHTF, initially developed by AFRL for its Miniature Munitions Technology, the predecessor to Small Diameter Bomb (SDB). The main modifications to the MEHTF design for STRIFE are:

- Replacing the MEHTF software driven safe and arm with a hardware only safe and arm for safety compliance.
- Improving the reliability of firing the MEHTF's Low Energy Exploding Foil Initiator (LEEFI) at cold temperature.
- Increasing the shock survivability of the MEHTF's LEEFI.

The Air Force continues to explore innovative techniques for intelligent burst point control by incorporating void-sensing capability into existing inventory fuzes as well as future weapons such as the HSP/CAV. The Hardened Miniature Fuze Technology (HMFT) program will commence in early calendar year 2006. The

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[7] "Low-Cost All-Electronic Penetration Fuze Exceeds Penetration Testing Objectives;" Success story, n.a. [AFRL/MN], "Multiple Event Hard Target Fuze Transitions to UK's Precision Guided Bomb Program," Mar 04.

[8] Program Research and Development Announcement Solicitation, n.a. [AFRL], "High Speed Penetrator," AFRL MNK-PRDA-02-0010, Jun 02.

objective of this program is to advance hardened miniaturized fuzing technology through the development of a survivable post-impact intelligent module and firing system that would become part of an overall fuze that is limited to a four cubic inch volume. This can be achieved by advancing the state-of-the-art in the areas of shock survivable components, packaging techniques, and testing technologies.[9]

The HMFT intelligent module will possess the capability of media discrimination (rock, concrete, soil, air, etc.) as the penetrator host progresses through the target and will incorporate a means of supplying post-impact data (target characterization data, bomb damage assessment information, and fuze arming information) to an external system. It is envisioned that this module could then be tailored for specific weapon applications by incorporating appropriate Safe and Arm (S&A) logic/devices. This tailoring may include use of the module as a command (remotely) armed device or by incorporation into a more conventional stand alone fuze.[10]

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[9] Broad Agency Announcement Solicitation, n.a. [AFRL], "Special Amendment for Fuzes Research, Hardened Miniature Fuze Technology," AFRL MNK-BAA-04-0001, Oct 05.

[10] *Ibid.*

Advanced Grid Stiffened Composite Payload Shroud

Since the beginning of the space age, satellites and other payloads launched into orbit have had their missions limited by such factors as weight, cost, and manufacturing time. The heavy metal shrouds or fairings that cover and protect payloads from atmospheric elements and launch winds have been of particular interest to scientists. Composite materials held the promise of lighter weight, durability, and reduced material and manufacturing costs, but needed better rigidity to use for complex shapes. Scientists at the Air Force's Phillips Laboratory achieved a remarkable breakthrough in the 1990s with the development of a technique called Hybrid Tooling that permits the necessary stiffening of the composite material and construction of complex payload shroud shapes through an automated, low-cost manufacturing process.

Spacecraft payloads launched from atop rockets require some measure of protection. Many payload components, such as antennas or deployable solar panels, are on the periphery of the spacecraft or are exposed. During launch, the rocket moves many times the speed of sound through the atmosphere, and the movement of air rushing by the payload, called a launch wind, can cause serious damage to the payload. Other equally damaging factors, such as rain, hail, or other moisture, could harm payload components. Unless the payload itself has a metal cocoon skin, a fairing or shroud is required to protect the payload from these elements. The earliest shrouds were constructed as a single piece of metal, usually aluminum, and built in a conical, aerodynamic shape. Later technologies created a honeycomb structure sandwiched between two metal skins. Once in space, the shrouds were jettisoned at the point of payload deployment into orbit.[1]

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[1]   History, PL/HO, "History of the Phillips Laboratory, 1 October 1989 – 30 September 1991" [hereafter cited as "History 1989-1991"], vol. I, 1992, pp.138-140; History, PL/HO, "Close-out History of the Phillips Laboratory, 1 October 1996 – 30 October 1997" [hereafter cited as "Close-out"], vol. I, 1998, pp. 791-793; Interview, Dr. Barron K. Oder, AFRL/VSIH, with Dr. Steven Huybrechts, AFRL/VS, 15 Jan 1998.

The increasing complexity of spacecraft missions has demanded more instrumentation, sensors, fuel, and power, all of which translates into increased weight and substantial lead time to build. Spacecraft designers have looked into reducing weight for all components, but especially from structural components such as the satellite bus and the payload shroud that do not add to the success of the mission. And because launch costs are measured in weight, an overall weight savings reduces overall costs.[2]

McDonnell-Douglas Corporation developed and patented isogrid shroud technology several decades ago. Aluminum isogrid structures, consisting of a shell or skin built from a single piece of machined aluminum stock bolstered with stiffeners that form equilateral triangles, have been used for launch vehicle shrouds and interstages on such common systems as the Atlas, Titan, and Delta rockets. But the open section metal isogrid shrouds are heavy, cost $16 million to produce, and require as much as two-and-a-half years' lead time to manufacture.[3]

Beginning in the 1970s, industry and academic researchers investigated the possibilities of using this isogrid technology with carbon fiber composite materials instead of metal to build a lighter payload shroud. In 1978, scientists at McDonnell-Douglas received a patent entitled "Stiffened Composite Structural Member and Method of Fabrication." The advantage of using composite materials in aerospace applications arises not only from lighter weight, but also

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[2]   "Close-out," pp. 791-793; Interview with Huybrechts, 15 Jan 1998.

[3]   "History 1989-1991," pp.138-141; Paper, James L. Koury and Thomas D. Kim, Phillips Laboratory, "Continuous Filament Wound Composite Concept for Space Structures" [hereafter cited as "Continuous Filament"], n.d; "Close-out," pp. 791-792; Paper, Dr. Steven Huybrechts and Troy E. Meink, Phillips Laboratory, "Advanced Grid Stiffened Structures for the Next Generation of Launch Vehicles" [hereafter cited as "Advanced Grid"], *IEEE Aerospace Applications Conference Proceedings,* vol. 1, 1997, pp. 263-269.

because composites have the ability to directionally enhance the shift in stress along the isogrid structure's ribs.[4]

NASA initially began to investigate the possibilities of composite isogrid technology during the 1980s. At the same time, the Soviet Union (later Russia) also experimented with the technology. Their scientists developed and even flew launch vehicle components made with composite isogrid technology, but they never fully achieved the desired weight savings. In part, this failure was due to their approach of using thicker, heavier ribs in the isogrid lattice. Although NASA used the composite skin to absorb the majority of the load, and used the grid lattice structure to suppress buckling, the final results did not meet expectations. American universities continued work in this area, but the efforts of private industry were sometimes unknown due to proprietary restrictions. By late in the decade, the European-built Ariane shroud, an aluminum-honeycomb sandwich structure with a composite skin, was the only composite shroud in use.[5]

Air Force laboratories began to investigate the potential of advanced grid stiffened composite technology during the late 1980s and early 1990s. Scientists at what would become part of Phillips Laboratory at Edwards Air Force Base, California, led efforts to build these lightweight composite isogrid structures, primarily geared toward satellite buses and solar panel substrates. In July 1990, they developed an experimental continuous-filament winding process that produced grid-stiffened structures using less expensive graphite and epoxy composite materials. By 1994, this group, which included scientists James Koury, Dr. Thomas Kim, and Dr. Peter Wegner, had resolved the prior manufacturing problem of carbon fiber buildup at the stiffener nodes connecting the lattice ribs. Their technique, which wrapped solid molded silicon rubber

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[4]   "Close-out," pp. 791-792.

[5]   "History 1989-1991," pp.140-141; "Continuous Filament;" "Close-out," pp. 792-793.

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sheets around a metallic mandrel, resulted in offset node points that reduced the fiber buildup. This process developed a high quality, lightweight composite isogrid structure that combined the structural efficiency of the isogrid design with the advanced properties of carbon fiber composite materials (in this case silicon rubber, with an extremely high strength to weight ratio). However, the manufacturing process was labor intensive, had problems with automation, and was limited to a cylindrical shape.[6]

The breakthrough in advanced grid stiffened composite payload shrouds began with the arrival of new personnel at Phillips Laboratory, Kirtland AFB, New Mexico. Mr. (later Dr.) Troy Meink, a researcher hired as part of the Air Force's Palace Knight program, was also an Air Force Reservist at the National Air and Space Intelligence Center (NASIC). As a reservist, Mr. Meink worked on an experimental NASIC project funded by the Ballistic Missile Defense Organization (BMDO) that needed to be launched at a specific apogee and altitude. Meink determined that a lighter payload shroud might provide the solution to reaching a higher altitude. As a scientist at Phillips Lab, he learned of the composite research being conducted by Dr. Steven Huybrechts. Dr. Huybrechts had graduated in 1995 from Stanford University, where he evaluated grid structures. Along with technician Master Sergeant Richard "Lee" Underwood, and the arrival of the Edwards AFB, California scientists, the group formed a highly successful team working at the Advanced Structures Laboratory at Phillips Lab.[7]

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[6] "History 1989–1991," pp.138-142; "Continuous Filament;" Paper, Thomas D. Kim and Peter Wegner, Phillips Laboratory Propulsion Directorate, "Composite Isogrid Structure," n.d.; Article, n.a., "Composite Isogrid Structures for Weight Savings and Lower Costs," *Phillips Laboratory Success Stories 1993-1994*, 1995, p. 99; "Close-out," pp. 793-794; "Advanced Grid," pp. 263-269.

[7] "Close-out," pp. 794, 800; Interview with Huybrechts, 15 January 1998.

Building upon the previous work of Phillips Lab scientists, this fortuitous confluence of need, new interest in the technology, recently available information, and the skills and abilities of the team yielded a concept called Hybrid Tooling in a relatively short period of time. The name "Hybrid Tooling" refers to the use of a variety of tooling materials. Much of this new development centered on moving away from traditional stiffeners using isosceles triangle patterns to develop more complex shapes and better manufacturing practices. Although most composite tooling material consisted of a single material, the team conducted extensive research to determine the most effective tooling materials. Combining materials permitted precise lateral rib compaction, while inserts could aid in building more complex shapes. In addition, the team used extensive mathematical modeling to build production tools.[8]

The Phillips Lab team first built a stainless steel base mandrel or spindle to support the base material, then covered it with a coarse tooling epoxy, and mounted this base tool structure to a filament winding machine. To automate the process, the team chose the computer-run five-axis filament winding machine because of its low cost and ability to accurately place filament fibers. They machined this base tool to the designed shape, including grid patterns for the ribs, but oversized the shape to accommodate the expansion inserts. The ribs, consisting of 12,000 carbon fiber strands pre-impregnated with uncured resin, were wound into a bundle by the filament winder and accurately placed into the grooves. Pre-sized silicon rubber expansion inserts were then hand-installed. Use of the inserts solved the team's greatest dilemma, that of controlling lateral compaction while still maintaining precise tooling tolerances and providing the desired cross-section geometrical shape. After the rib winding was complete, the skin was wound, using additional composite tape and fiber applied at critical locations where stress was concentrated, such as the bolts. Once the winding

[8]   "Close-out," pp. 794-796; Interview with Huybrechts, 15 Jan 1998; "Advanced Grid," 1997, pp. 263-269.

was completed, the part was placed in a vacuum bag and heated to cure the epoxy. Following the curing process, the team returned the part/tooling combination to the filament winder for accurate computer-controlled finish trimming and machining. With some repair, the team found that the tooling could be reused to construct a similar shroud. The team also determined that the fully automated process led to a substantial reduction in manufacturing time and could be easily scaled for different-sized shrouds.[9]

The Phillips Lab team developed this first conical shroud for NASIC's second BMDO-sponsored Combined Experiments Flight. Fortunately for the Phillips Lab team, NASIC accepted the shroud as just another experiment on their flight, and as a relative newcomer to the field, launch contractor Optical Sciences Corporation was more easily accepting of new technology. To gain the launch contractor's acceptance, the team over-designed the shroud and built it stronger than necessary, submitting it to Orbital for qualification testing in October 1996. Under normal circumstances, qualification testing means reaching to within 75% of a device's failure point, and then tossing out the used test device. However, Orbital could not break the shroud and felt that since there was no need to test to failure, they considered it flight worthy, and did not require construction of a new shroud. The suborbital Combined Experiments Flight successfully launched from the Wallops Island, Virginia facility on 23 February 1997 and the shroud lived up to the team's high expectations in protecting the payload.[10]

Since advanced grid stiffened (AGS) composite technology was new, Orbital had already prepared an aluminum shroud, which gave the lab a good direct comparison with older technologies. When first designed, the lab's shroud had an

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[9] "Close-out," pp. 796-798; Interview with Huybrechts, 15 Jan 1998; "Advanced Grid," pp. 263-269.

[10] "Close-out," pp. 799-803; Interview with Huybrechts, 15 January 1998.

overall weight of 37 pounds. To obtain Orbital's approval, the team built it with three times the buckling load as well as ten times the stiffness of what they considered safe levels, so the final weight reached 82 pounds. Indeed, when the contractor crew lifted it from its shipping crate, they were so startled at its lightness that they almost dropped it on the spot. The aluminum shroud weighed 212 pounds, giving the new device a remarkable 61% weight savings. It took the team about a year to develop the tooling technology, but it only took about a month to design the shroud. Assembly and part fabrication took nine days compared to 75 days needed to build the aluminum shrouds, an 88% improvement. And with launch costs at approximately $10,000 per pound, the monetary savings proved equally remarkable. The estimated overall R&D costs, including salaries, reached $600,000, with another $90,000 for testing. Based on this comparison, the team felt that the real payoff was the much-improved and more-automated Hybrid Tool manufacturing process that used less time with less money and could be adapted for use with more complex conical or double curvature shapes, and scalable for different sized shrouds.[11]

AGS technology and the Hybrid Tooling method have received serious attention and recognition. Although the lab had attempted to get industry's support when the project first began, within a week after trade journals publicized the successful NASIC launch, several major launch vehicle manufacturers flooded the team with inquiries. The Air Force team holds the AGS technology and technique patents. Air Force Materiel Command, parent organization for the laboratory system, awarded the team its prestigious Science and Technology award for 1997. For his part, Dr. Huybrechts received the 1999 Arthur S. Flemming Award recognizing young federal government employees in areas of basic science and administration, while in 2001, team member Dr. Peter Wegner also received the Flemming award and DoD's prestigious Harold Brown Award in 2003. In 1999, the Air Force Research Laboratory (AFRL) – the single Air Force

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[11]   "Close-out," pp. 798-802; Interview with Huybrechts, 15 Jan 1998.

Laboratory formed from the Phillips Lab and other AF labs and R&D organizations -- named its Space Vehicles Directorate's Spacecraft Components Technology Branch a center of excellence for this and other structural work.[12]

After the initial breakthrough, AFRL composite scientists continued to advance the AGS effort, especially in moving it toward production-oriented applications such as transitioning it to a major launch system and adapting it for both expendable and reusable launch vehicles. In 1999, the Boeing Company expended $500,000 to transition the technology, notably as a replacement for the Delta II interstage fairing, while CSA Engineering worked on acoustic suppression systems for AGS structures. The same year, AFRL began to baseline AGS technology for the Minotaur launch vehicle. By 2000, AFRL's Space Vehicles Directorate, working with the Boeing Phantom Works, had fabricated a large composite shroud for the Space and Missile Systems Center's Orbital/Suborbital Program Minotaur Launch Vehicle. This demonstration validated improved methods for fiber placement of ribs and skin, the termination of the ribs at the fairing's fore and aft ends, and shaping the fairing's boat-tail section to its cylindrical section. The fairing doubled the existing volume capability of the Minotaur launch vehicle, adding only slightly to its overall weight while successfully meeting acoustic mitigation. In 2002, Boeing delivered the Minotaur fairing to AFRL for flight qualification tests. The fairing's applied load exceeded the worst case dynamic flight conditions by 25%, and maintained

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[12] Interview with Huybrechts, 15 Jan 1998; "Close-out," pp. 803, 807; Rpt, n.a., "AFRL Monthly Accomplishment Report, Executive Summary," Aug 2002; History AFRL/HO, "History of the Air Force Research Laboratory, 1 October 1999 – 30 September 2000," vol. I, 2002, pp. 383-384. Article, AFRL/XPTC, "Tab 4—Awards and Recognition: Dr. Huybrechts Wins Arthur S. Flemming Award for Structures Research," *Air Force Research Laboratory Success Stories, A Review of 2000*, 2001, pg. 15; Article, AFRL/XPTC, "Tab 4—Awards and Recognition: Dr. Peter Wegner Receives the Harold Brown Science and Technology Award," *Air Force Research Laboratory Success Stories, A Review of 2003*, 2004, p. 58.

structural integrity under the peak load. Failures with substructure test panels led to stabilizing the skin/rib interface without increasing the fairing's mass.[13]

In creating the Hybrid Tooling method to build an advanced grid stiffened composite payload shroud, the Air Force laboratory team took a technology that many saw had potential but were unwilling to trust, developed and tested it as a worthy application, then turned it over to industry for use on military and commercial systems. Advanced Grid Stiffened Composite technology has already proven its structural efficiency, high damage tolerance, and propensity toward automated manufacture. And although there are other new composite shroud technologies competing for industry's attention, the Air Force developed and has transitioned this cost-effective, innovative, flexible breakthrough.

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[13]   Notes/comments, Jeffry S. Welsh, AFRL/VSSV, "on Advanced Grid Stiffened Composite Payload Shroud draft," 28 July 2005; Paper, Peter M. Wegner, Jeff M. Ganley, Steven M. Huybrechts, and Troy E. Meink, "Advanced Grid Stiffened Composite Payload Shroud for the OSP Launch Vehicle," *IEEE 2000 Aerospace Conference Proceedings*, March 2000, pp. 359-365; Article, AFRL/XPTC, "Tab 3—Technology Transfer: Advanced Grid Stiffened Structures Lower Launch Costs," *Air Force Research Laboratory Success Stories, A Review of 1999*, 2000, p. 35; Article, AFRL/XPTC, "Tab 2—Emerging Technologies: Advanced Grid-Stiffened Composite Fairing," *Air Force Research Laboratory Success Stories, A Review of 2000*, 2001, p. 50; Article, AFRL/XPTC, "Tab 2—Emerging Technologies: Experimental Testing of Advanced Grid-Stiffened Structures," *Air Force Research Laboratory Success Stories, A Review of 2002*, 2003, p. 50; Article, AFRL/XPTC, " Tab 2—Emerging Technologies: Minotaur Advanced Grid-Stiffened Composite Fairing," *Air Force Research Laboratory Success Stories, A Review of 2004*, 2005, p. 73.

Adaptive Optics

Development of laser guide star technology was an extremely important Air Force Weapons Laboratory (AFWL) contribution to the advancement of adaptive optics. Advanced adaptive optical systems sought to remove distortions in light waves created by atmospheric turbulence, but early systems consumed most of the light to measure wavefront distortions, leaving an insufficient amount of light from the object to send to a camera to produce a clear image. Military scientists believed that if the distortion could be accurately measured, an adaptive optics system could be developed using light from an artificial beacon—instead of from the viewing object—to compensate for the distortions, resulting in clearer images.

In 1983, Dr. Robert Q. Fugate led a team of AFWL scientists at Starfire Optical Range at Kirtland AFB and proved for the first time the physics of the laser guide star technique to accurately measure atmospheric turbulence. Artificial laser guide star adaptive optics is a breakthrough technology used for two purposes: imaging dim objects, using incoming light from space objects, such as stars, satellites, or missiles, to identify and produce razor-sharp images of those objects; and directing outgoing light, in the form of a high-quality laser beam, through the air to intercept a moving target.[1]

As light travels from an object in space to an earth-bound telescope, the light is distorted because of atmospheric turbulence. Atmospheric turbulence is caused by random localized fluctuations in the temperature and density of the air.

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[1] Interview, Dr. Robert W. Duffner, AFRL/VSIH, with Dr. Robert Q. Fugate, AFRL/DE, 16 Dec 2002; Article, Dr. Robert Q. Fugate, et al., "Measurement of atmospheric wave-front distortion using scattered light from a laser guide-star" [hereafter cited as "Atmospheric wave-front"], *Nature*, 12 Sept 1991, pp. 144-146; Paper, Dr. Robert Q. Fugate, "Experimental Demonstration of Real Time Atmospheric Compensation with Adaptive Optics Employing Laser Guide Stars," presented at the American Astronomical Society meeting, 27 May 1991.

The twinkling of starlight is perhaps the most widely known manifestation of the effects of atmospheric turbulence on light propagation. The laws of physics dictate that turbulence can severely impact the performance of imaging systems and high-energy laser weapon systems. Astronomical telescopes must be large enough to collect sufficient light to detect and image dim objects. But atmospheric turbulence has always limited the resolution of an image produced by a large telescope, such as the ability to distinguish the stars in a binary star, to a resolution no better than that of a small amateur backyard telescope. Laser beams as a form of light are electromagnetic waves, and an electromagnetic wave can be described in terms of its amplitude and phase or wavefront. Just as a distorted wavefront can degrade the performance of an imaging system, producing an out of focus picture, a distorted wavefront can limit the intensity of a high-energy laser at its target and prevent the delivery of the desired amount of energy to destroy the target.[2]

The solution to each of these technical dilemmas is the use of adaptive optics. Adaptive optics refers to an optical system that can adapt the shape of a mirror in such a way that when incoming light is reflected from it, either to a camera or as an outgoing laser beam, the distortions caused by atmospheric turbulence are removed to maintain the high quality of an image or a beam of light. In 1953, astronomer Horace Babcock first proposed using adaptive optics for large telescopes to reach their full potential. Adaptive optics would establish real-time compensation of distorted light to create higher image resolution. However, the approach he proposed was not really practical and was never implemented.[3]

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[2]   Interview, with Fugate, 7 Nov 2005; Interview, Duffner with Dr. Rett Benedict, Vice President of the Space and Directed Energy Division, Schafer Corp., 28 Oct 2002; Rpt, Glenn A. Tyler, et al., The Optical Sciences Company, "Adaptive Optics: Theory and Applications," AFRL-DE-PS-TR-1998-1054, Pt. 1, Dec 1999, pp. 2-8.

[3]   Interview, Duffner with Raymond P. Urtz, Director, AFRL/IF, 20 Nov 2002; Article, Roger Angel and Dr. Robert Q. Fugate, "Adaptive Optics," *Science*, 22 April 2000, p.

National defense requirements drove much of the progress in adaptive optics beginning after the discovery of the laser in 1960. The Department of Defense, and the Air Force in particular, became interested in adaptive optics for its potential to improve performance of space-object imaging systems and for possible future laser weapons. In the mid-1960s, Rome Air Development Center (RADC), part of the Air Force laboratory system, conducted early experiments to define the effects of atmospheric turbulence on light and on laser beams. RADC and its contractor Itek accomplished a real time, higher-order compensation of atmospheric turbulence using a deformable mirror in 1974. The Real Time Atmospheric Compensation (RTAC) system initially corrected a laser beam propagated through atmospheric turbulence over a 300-meter path to a 30-centimeter aperture. RTAC consisted of three components essential to an adaptive optics system: a shearing interferometer wavefront sensor to detect and measure the atmospheric distortions impressed on a light wave; a high-speed controller system, essentially a fast computer; and a deformable mirror whose reflective surface and shape were altered by 21 actuators to correct for the turbulence-affected light, based on light distortion measurements fed to it by the computer. The combination of RTAC's mirror and the wavefront sensor represented breakthrough advances in the state-of-the-art adaptive optics hardware.[4]

After the success of RTAC, RDAC continued to make significant progress in the development of more advanced adaptive optical systems. In 1982, RADC installed the first practical adaptive optics system, the compensated imaging system or CIS, on the 1.6-meter telescope at the Advanced Research Projects

455; Article, H.W. Babcock, "The Possibility of Compensating Astronomical Seeing," *Astronomical Society of the Pacific*, Oct 1953, pp. 229-236.

[4] Interview with Urtz, 20 Nov 2002; Interview, Duffner with Dr. Don Hanson, Director, AFRL/SN, 19 Nov 2002; Interview, Duffner with Dr. John W. Hardy, Retired, Itek, 22 Jan 2004; Article, John W. Hardy, "Adaptive Optics," *Scientific American*, June 1994, p. 63.

Agency Maui Optical Site (AMOS) located atop Mt. Haleakala. The workhorse CIS unit used a deformable mirror with over 100 actuators and provided compensated images of space objects continuously into the 1990s.[5]

Despite these advances, the adaptive optics wavefront sensor consumed most of the object's available light, leaving an insufficient amount of the collected light to form a high quality image of the observed object. Furthermore, the vast majority of space objects viewed by ground telescopes appeared dimly, providing insufficient photons for effective compensation. Consequently, military scientists began to search for new ideas and techniques to maximize the use of available natural light. In the early 1980s, DARPA, the Defense Advanced Research Projects Agency, funded military-related adaptive optics research to explore ways to acquire more light to produce higher resolution images.[6]

One innovative approach that quickly gained favor with DARPA and other researchers was contractor Julius Feinleib's concept of using an artificial, independent light source or laser guide star to measure the atmospheric turbulence at lower levels of the sky, where most of the distortion occurs. The laser guide star he proposed relies on a principle of physics called Rayleigh backscattering, named for astronomer John William Strutt, Lord Rayleigh (1842-1919). When a laser is aimed directly at an object in space, the backscattered light from the focused laser (as it strikes nitrogen and oxygen molecules in the atmosphere) and natural light from the object both travel along near-identical paths and encounter the same atmospheric turbulence on the way to a telescope. The light that returns from the focused laser beam serves as an

[5] Interview with Hanson, 19 Nov 2002; Interview with Urtz, 20 Nov 2002; Rpt, n.a., "FY82 Accomplishments," RADC-TR-82-1, Dec 1982, pp.8-9.

[6] Interview with Benedict, 28 Oct 2002; Interview, Duffner with Dr. William E. Thompson, AFRL/DET, 9 Oct 2002.

artificial star, hence the name laser guide star. By sampling only the backscattered laser light to make corrections and to compensate for the distortions, all of the object's small amount of natural light could then be collected by the telescope, reflected from the deformable mirror and sent directly to the imaging camera, forming a clear image.[7]

However, scientists were concerned about the location of the guide star. Measuring Rayleigh backscattering meant placing the laser guide star at no more than 10 to 20 kilometers in the sky, but atmospheric turbulence extended well beyond that range. DARPA's 1982 solution, guided by the military's independent science colloquium called the JASONs, was to move in both directions, that is, to measure turbulence at the lower Rayleigh level using essentially any laser beam as the guide star, as well as using a laser beacon at an altitude of 90-100 kilometers, where a layer of atomic sodium could be probed only by a sodium wavelength laser. The Air Force Weapons Lab conducted the Rayleigh experiment, while the Massachusetts Institute of Technology's Lincoln Laboratory tested the sodium method. The potential success of this revolutionary technology, including breakthroughs in imaging of space objects such as enemy satellites, kept this research classified until May 1991.[8]

Dr. Robert Q. Fugate, with previous experience in Rayleigh physics at the Air Force Avionics Laboratory, arrived at the Weapons Lab in 1979. His initial work consisted of beam control research by measuring the effects of air turbulence on low-power lasers at the Sandia (later Starfire) Optical Range or SOR at Kirtland AFB. AFWL leadership selected Fugate to conduct a proof-of-concept experiment to validate that the Rayleigh artificial guide star would work in the real

[7] Interview, Duffner with Dr. David L. Fried, 2 April 2003; Interview with Fugate, 16 Dec 2002; Interview with Hardy, 22 Jan 2004.

[8] Interviews, with Fugate, 2 April 2003 and 20 May 2003; Rpt, Glenn A. Tyler, et al., The Optical Sciences Company, "Adaptive Optics: Theory and Applications," AFRL-DE-PS-TR-1998-1054, Pt. 1, Dec 1999, pp. 10-11.

world. Fugate's team chose a short wavelength visible green laser for the laser guide star (shorter wavelengths produced more backscattering for better measurements) to be focused at a distance of five kilometers into the sky and directly pointed at the star Polaris.[9]

Following construction of the experimental equipment, including a 60-centimeter tracking mirror at the SOR in the fall of 1982, the AFWL team began testing the next spring. The experiment ran over a long period of time to account for a wide range of different atmospheric conditions and to collect comparative data. By the late summer and fall of 1983, the team consistently measured atmospheric distortion from the laser by comparing those figures to the measurements from Polaris. Measurements from Polaris and the Rayleigh beacon showed a good match. That was a major turning point because the AFWL data validated the theoretical physics behind an artificial laser guide star for the first time.[10]

Nevertheless, Fugate's experiment was not conducted using an operational adaptive optics system, although its success provided the impetus for a "closed-loop" or complete system. In 1987, AFWL acquired and installed a 1.5-meter telescope at the SOR. Integrating this telescope with a wavefront-sensor, a high-speed computer processor, and a deformable mirror led to research that corrected for atmospheric distortions, which occurred in real-time. In 1989-1990, Fugate and his team conducted the first successful closed-loop series of adaptive optical experiments using the Rayleigh laser guide star technique,

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[9] Interview, with Fugate, 22 April 2003; Interview with Benedict, 28 Oct 2002; "Atmospheric wave-front," pp. 144-146.

[10] Interviews, with Fugate, 16 Dec 2002, 21 April 2003, and 20 May 2003; "Atmospheric wave-front," pp. 144-146.

called Generation I, followed by Generation II experiments between February and May of 1992.[11]

Lincoln Laboratory began its sodium-beacon experiment at White Sands Missile Range using a dye laser tuned to the sodium wavelength in 1984. In 1985, Lincoln Lab succeeded in demonstrating that a sodium-wavelength beacon could measure atmospheric turbulence at higher altitudes, offering a more complete picture of distortion than the Rayleigh beacon. This success was followed by Lincoln Lab's own successful closed-loop system at the Air Force Maui Optical Site (AMOS) in 1988. Further, theoretical calculations showed that atmospheric compensation for larger telescopes in the range of 3-plus meters worked well with a sodium wavelength system. The success of AFWL's 1.5-meter system, along with results of the sodium experiment, paved the way for a larger 3.5-meter device built and completed in 1993 at SOR by AFWL's descendent, Phillips Laboratory.[12]

Despite these military-directed scientific advances, results remained classified and unknown to the outside world. But civilian astronomical research began to close in on the same results, so the various parties, including AFWL, DARPA, and the JASONs, decided to declassify the guide star experiments. At a meeting of the American Astronomical Society in May 1991, Fugate and his

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[11]   Interview, with Fugate, 5 April 2004; Lab notebook, Dr. Robert Q. Fugate, "entry for 13 Feb 1989," 1989; Article, Dr. Robert Q. Fugate, et al., "Two generations of laser-guide-star adaptive-optic experiments at the Starfire Optical Range," *Journal of the Optical Society of America*, vol. 11, No. 1, Jan 1994, pp. 310-312; Ltr, Maj Gen Robert R. Rankine, Jr., DCS/Technology, AFSC, to PL/CC, "subj: Laser Guide Star Adaptive Optics," 19 June 1992.

[12]   Interview, Duffner with Dr. Darryl P. Greenwood, Lincoln Laboratory, 21 Jan 2004; Interview with Benedict, 28 Oct 2002; Article, Charles A. Primmerman, et al., "Compensation of atmospheric optical distortion using a synthetic beacon," *Nature*, vol. 353, 12 Sept 1991, pp. 141-143; Article, Byron G. Zollars, "Atmospheric-turbulence Compensation Experiments Using Synthetic Beacons," *Lincoln Laboratory Journal*, Spring 1992, pp. 67-77.

Lincoln Laboratory counterparts revealed their results to an astounded and at first disbelieving scientific audience. But reproducible science proved the veracity of the Air Force and DoD researchers, garnering national and international attention. In particular, Dr. Fugate emerged as a world-class leader, and the Air Force's laboratory system achieved a world-class reputation in the field of adaptive optics.[13]

The practical scientific principles of these experiments were quickly applied to the Air Force's Airborne Laser (ABL). The ABL program, which began in the early 1990s, required improving the acquisition, pointing, and tracking system of the first-generation Airborne Laser Laboratory, which was successful in targeting and destroying air-to-air missiles and ground-to-air drones in 1983. The ABL high-energy laser weapon system must propagate a beam over hundreds of kilometers horizontally at operational altitudes of over 40,000 feet to destroy its target. Adaptive optics provided the potential answer to compensating for atmospheric turbulence at those heights. Since the early 1990s, Phillips Laboratory, which then became part of the Air Force Research Laboratory, conducted a series of experiments designed to collect and measure atmospheric turbulence data, to evaluate the propagation of the laser beam through the atmosphere, and to compensate for those distortions that affected the quality of the beam. The results of all of these experiments validated the use of adaptive optics in an airborne laser weapon system.[14]

The first ever laser guide star experiments conducted by Dr. Fugate's Air Force Weapons Laboratory team at the Starfire Optical Range in 1983 provided

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[13]   Interview, with Fugate, 13 July 2004; Paper, Dr. Robert Q. Fugate, "Experimental Demonstration of Real Time Atmospheric Compensation with Adaptive Optics Employing Laser Guide Stars," 27 May 1991.

[14]   Interview, Duffner with Dr. Laurence D. Weaver, AFRL/DEBA, 6 Nov 2000; Rpt, Lawrence D. Wheeler, et al., "ABLESTAR," AFRL-DE-TR-1024, April 2002, pp. 1-2.

a tremendous breakthrough in the realm of adaptive optics. Although researchers had advanced the field through the development of wavefront sensors, deformable mirrors, and the use of high-speed processors, the experiments conducted by AFWL and Lincoln Laboratory permitted the use of far-reaching techniques that improved astronomical-related systems in both the civilian and military scientific communities. Today every large telescope uses adaptive optics to obtain higher resolution images, often relying on sodium-wavelength beacon technology to resolve dimmer objects. Moreover, potential laser weapon systems depend on the same adaptive optical technology to provide accurate, on-target delivery of lethal laser energy.[15]

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[15]   Interview, with Fugate, 7 Nov 2005.

AFRL and the ARPANet

The development of the Internet in the last third of the 20th century is arguably the most revolutionary event in communications since the invention of the telegraph and telephone in the 19th century. The Internet represents the convergence over three decades (1960s through 1990s) of a number of different ideas and technologies, including the telegraph, telephone, and digital computer.[1] It also represents the successful collaboration of government, academic, and commercial enterprises.

The forerunner of the Internet was the ARPANet. The development of ARPANet was initiated and underwritten by the Advanced Research Projects Agency (ARPA). ARPA was established in 1958, at a time when U.S. confidence in its science and engineering establishment was momentarily shaken by the Soviet Union's success in launching the first artificial earth satellite, *Sputnik*, in 1957. ARPA's purpose was to initiate scientific research in potentially high pay-off areas.[2]

In the early 1960s, ARPA sponsored research into emerging computer technologies. One aspect of the research was a concept called "time-sharing," which allowed smaller computer centers to use the computing capabilities of larger computer facilities via telephone lines. This diminished the need to

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[1] Article, Barry M. Leiner, Vinton G. Cerf, David D. Clark, et al., "A Brief History of the Internet," n.d., at www.isoc.org/internet/history/brief.shtml, as of 29 Oct 05.

[2] At first, ARPA's projects were not specifically or necessarily defense related. They focused, rather on generic areas of research of national importance. However, defense needs increasingly preoccupied ARPA's agenda so that in 1972, it was renamed the *Defense* Advanced Research Projects Agency (DARPA). The organization remained DARPA until the Clinton administration returned it to ARPA in 1993, following the end of the Cold War. In 1996 the agency was redesignated DARPA. See Article, n.a., "ARPA-DARPA – the History of the Name," 27 Oct 03, at www.darpa.mil/body/arpa_darpa.html, as of 5 Dec 05.

purchase large, costly computers at each and every location.[3] ARPA contracted with the Massachusetts Institute of Technology (MIT) and the University of California, Berkeley, to develop the time-sharing concept.

At about the same time, the U.S. Air Force (USAF) commissioned the RAND Corporation to study how the Air Force could maintain command and control over its strategic arsenal in the event of a nuclear attack. RAND proposed a "packet switched" network. Packet switching segmented messages into information packets before routing them to their ultimate destinations, where switches reconstructed the packets back into messages and delivered them to specific addresses. If the packets were lost at any given point, they could be resent by the originator. The entire operation could be accomplished in less than a second.[4]

The two operations, time-sharing and packet-switching, underlay the deployment of the ARPANet and later the Internet.

The Air Force Research Laboratory's Information Technology Directorate's predecessor organization, the Rome Air Development Center (RADC), became involved in ARPANet as a result of its responsibility for the Air Force's exploratory development of computer technology for command and control.[5] As a result, RADC played a leading role in developing computer network technologies for the Air Force.[6]

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[3]   Book, Thomas W. Thompson, *The Fifty-Year Role of the United States Air Force in Advancing Information Technology—A History of the Rome, New York, Ground Electronics Laboratory* [hereafter cited as *HRL*], Studies in Twentieth Century American History, vol. 10 (Lewiston, Queenston, Lampeter: The Edwin Mellen Press), n.d., p. 117.

[4]   *HRL*, p. 118; Article, Dave Kristula, "The History of the Internet," Aug 2001, at www.davesite.com/webstation/net-history.shtml as of Oct 28 2005.

[5]   *HRL*, p. 114.

[6]   *HRL*, p. 117.

In 1966 RADC inaugurated time-sharing in Air Force computer networks with the purchase of the General Electric 645 Computer running the General Comprehensive Operating System (GCOS). This was the first computer ordered specifically by a military service that was designed specifically for time-sharing operations. The GE 645 was capable of hosting four central processors and could be modified to incorporate specialized components and peripheral equipment. It was intended for conducting research into Air Force command, control, intelligence, and information management systems.[7]

In October 1966, RADC announced the Cooperative Program, a plan to begin time-sharing with 18 New York state universities. Under the program, which was partially funded by the National Science Foundation, the universities shared access to the GE 645 computer through remote access terminals and modems to use existing telephone lines.[8]

Two years later, in 1968, RADC expanded time-sharing capabilities with the capability of operating different kinds of computer languages. The following year, RADC began using the Multiplexed Information and Computing System (MULTICS) with the GE 645. MULTICS increased security and made it easier to operate RADC's time-sharing service.[9] The MULTICS system was upgraded to the Honeywell 6800 series in the 1970s and the DSP 8/M series in the 1990s.

Meanwhile, the Department of Defense (DOD) and ARPA noted RADC's research in time-sharing and packet-switching in command and control and became interested in using them as a possible method of integrating computers

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[7] *HRL*, p. 118.

[8] *Ibid.*

[9] *HRL*, pp. 118-19.

operating at different locations. ARPA, in particular, was interested in "teleprocessing," which would link dissimilar computers into networks through packet-switching with the goal of reducing system vulnerability by distributing computers and their supporting equipment over a wide area.[10]

In December 1968, ARPA awarded a contract to Bolt, Beranek and Newman (BBN) to build such a distributed area network, to be called ARPANet.[11] In 1969, ARPANet was initially brought on line[12] and by 1971 was fully up and running.[13] By this time, ARPANet included 21 computer centers, including the University of Southern California, Los Angeles (UCLA); Stanford Research Institute; the University of California, Berkeley; the University of Utah; the Massachusetts Institute of Technology; Harvard University; the Systems Development Corporation, Santa Monica, California; Carnegie Mellon University; Case Western Reserve; NASA-Ames; MITRE; Burroughs; RAND;[14] the University of Illinois—and RADC.[15] RADC joined the ARPANet as the 18th node on October 5th, 1971.

ARPA was able to show that, as with surveillance sensors and communications, computers could also demonstrate dispersal over great distances, a phenomenon that became known as "distributed computing." What distributed computing did was to allow not only the computerization of separate

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[10]   *HRL*, p. 119.

[11]   *Ibid.*

[12]   Article, Walt Howe, "A Brief History of the Internet" [hereafter cited as Brief History"], 14 Sep 04, at www.walthowe.com/navnet/history.html, as of Oct 28, 2005.

[13]   *HRL*, p. 119.

[14]   "Brief History," p. 2.

[15]   *HRL*, p. 119.

surveillance, communications, and intelligence centers, but also integrating them into a single network.[16]

The ARPANet grew from 3 nodes in 1969 to 21 by 1971. Each node at a site could have up to several different computer systems connected to it. By 1982 there were 88 sites. In the early 1980s the Message Control Protocol (MCP) that the connected systems used as the common network language was phased out in favor of a more robust four-layered network protocol stack based on the Transmission Control Protocol/Internet Protocol (TCP/IP). TCP/IP allowed for the "internetworking" of different computer network technologies. By 1989 it had spawned the internetworking of hundreds of networks (including a sister network MILNet, a satellite version SATNet, and a terrestrial WIDEBAND) and allowed thousands of computers and millions of users to communicate with each other.[17]

In early 1989, the ARPANet core was replaced in favor of five higher-speed region-based networks unified by a backbone managed by the National Science Foundation. This was called the Defense Research Internet (DRI). The regional networks were run by consortiums of colleges and universities. NYSERNet covered the northeastern United States and was sponsored by RADC. By the late 1990s these mutated into commercial services such as PSINet and were joined by larger Internet Service Providers (ISPs) such as Sprint, MCI, and AOL. The ARPANet was officially shut down at midnight on 28 February 1990.[18]

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[16] *HRL*, p. 119.

[17] E-mail, Mark Lomery, AFRL/IFOI, to Dr. James F. Aldridge, AFRL/HO, "Write-Ups for McFawn Project/Arpanet, atch: ARPANET – Gubbins & Debaney.doc" [hereafter cited as "Write-Ups"], 22 Nov 05.

[18] *Ibid.*

RADC took the concept of distributed computing to the next level in 1981 when it began working with BBN on CRONUS, a distributed operating system overlaid on existing computer systems that was capable of performing complex command and control operations, thereby reconciling differences in computer systems so that they operated as if they were a single system. Under CRONUS, local area networks (LANs) (see below) connected computers at specific locations while wide area networks linked them over greater distances. By the end of the 1980s, CRONUS ran approximately 100 computers, located at eleven sites.[19]

In cooperation with ARPA, the Defense Communications Agency, and the USAF Strategic Air Command (SAC), RADC investigated the feasibility of using distributed computing for strategic military communications. Under the Strategic Command, Control, and Communications (C^3) Experiment, RADC tested packet switching and other distributed computing technologies for their potential in reconstituting communications networks in the event of a national crisis. Subsequently, under the Survivable Adaptive Planning Experiment (SAPE), RADC sought to apply distributed computing technology to tasks associated with generating SAC's Single Integrated Operational Plan (SIOP). By so doing, RADC demonstrated that distributed computing enhanced U.S. nuclear deterrence by dispersing computing systems, thereby making them more survivable in the event of an attack. The technology thus enhanced command and control by allowing the networking of computers among widely deployed forces.[20]

In addition to distributed computing, RADC also made major contributions, both conceptually and technically, to the development of LANs. These networks integrated computers at specific locations and provided the means of

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[19]   *HRL*, pp. 119-20.

[20]   *HRL*, p. 120.

"internetworking" distant databases and networks, connecting computer users to "global" systems.[21] One RADC LAN was the Flexible Intraconnect Local Area Networks (FILANS), which employed laser and modular components that made LAN technology more reliable and easier to deploy.[22]

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[21] *HRL*, p. 121.

[22] *HRL*, p. 122; "Write-Ups".

Airborne Laser Laboratory

The development of the Airborne Laser Laboratory (ALL) was one of the most extraordinary achievements in the annals of science and engineering. A highly dedicated team of talented military and civilian scientists at the Air Force Weapons Laboratory (AFWL), Kirtland Air Force Base, New Mexico, succeeded in testing and operating a high-power CO_2 gas dynamic laser integrated with a precision pointing and tracking system aboard a specially modified NKC-135 aircraft known as the ALL. In May 1983 over the Naval Weapons Center Range at China Lake, California, the ALL shot down five AIM-9 "Sidewinder" missiles. Four months later, the ALL's laser beam intercepted three Navy BQM-34A drones over the Pacific near Point Mugu, California. The success of these demonstrations proved for the first time that an airborne laser could intercept and destroy aerial targets and showed the potential of high-energy lasers as airborne weapons.

A laser, or *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation, is the most concentrated and powerful form of light known. An intense energy source excites a selected gas, liquid, or solid substance so it is capable of lasing, and a resonator with mirrors at each end extracts the optical energy in the form of a beam. The advantages of lasers are delivering large amounts of energy to a very small area, and traveling over long distances at the speed of light. Additionally, a concentrated laser beam minimizes collateral damage to nearby structures and greatly reduces the potential for civilian casualties. But there are major difficulties in developing airborne laser weapons. Lasers need enormous power to generate a beam of sufficient lethal energy. Atmospheric absorption of the laser beam decreases its power, and heating the beam in the air distorts and deflects it. Laser light randomly spreads out in all directions, which requires focusing the beam with optical mirrors. Keeping the beam steady must occur at

the same time the laser platform and target are maneuvering and moving at high speeds.[1]

The roots of the ALL program stretched back to the early 1960s. Dr. Theodore Maiman, a senior scientist at Hughes Aircraft Company's Research Laboratory, generated the world's first laser beam on 15 May 1960. Recognizing the potential military payoffs for lasers, the Department of Defense's Advanced Research Projects Agency (ARPA) funded laser research at the Air Force Special Weapons Center (AFSWC) in February 1962. By 1963, AFSWC's work on solid state lasers proved disappointing. But between 1964 and 1967, commercial researchers discovered that molecular gas carbon dioxide could be used as a lasing medium and developed a CO_2 gas dynamic laser or GDL. These breakthroughs, with their potential for higher power levels and reduced device weight, offered the most promise for military applications.[2]

As early as 1965, AFSWC's descendent, the Air Force Weapons Laboratory, began pursuing the idea of putting a laser on an aircraft. Recognizing the advantages and disadvantages of lasers, the lab knew that the development of any high-power laser system required perfecting the technology for a variety of subsystems. Although the laser device could produce a lethal beam, a search

[1] Book, Robert W. Duffner, *Airborne Laser: Bullets of Light* [hereafter cited as *Airborne Laser*], (New York: Plenum Press), 1997, p. 6; Rpt, Col John C. Scholtz, Jr., "The Air Force High Energy Laser Program," Air War College Professional Study No. 4229, Nov 1970, pp. 1-6; Rpt, Physics Department, Air Force Institute of Technology, "Laser/Optics Short Course," June 1979; Article, Arnold L. Bloom, "Optical Pumping," in Book, Schawlow, ed., *Lasers and Light* (San Francisco: W.H. Freeman & Co.), 1969, pp. 46-54.

[2] *Airborne Laser*, pp. 2, 12-18; Interview, Dr. Robert W. Duffner, AFWL/HO, with Maj Gen Donald L. Lamberson, USAF, Office of the Assistant Secretary of the Air Force for Acquisition, 12 Jan 1989; Article, T.H. Maiman, "Stimulated Optical Radiation In Ruby," *Nature*, 6 August 1960, pp. 493-494; Ltr, J.P. Ruina, Director, ARPA, to Commander, Office of Aerospace Research, "ARPA Order 313-62," 26 Feb 1962; Rpt, n.a., "Advanced Development Plan: Gas Dynamic Laser Weapon," WLRE-67-170, Sept 1967, pp. A-1—A-2.

and acquisition subsystem had to locate and start tracking the target, then the tracking function would be transferred to a precision pointer and tracker. A beam control system consisting of an intricate series of mirrors would transmit the beam from the laser device to the pointer and tracker, which focused the beam with a large primary mirror and aimed and directed the beam to hit the target. Although the concept sounded simple, AFWL understood that integrating these distinctly different components into one harmonious system would be an extremely difficult challenge. Also, the lab intentionally structured its research to proceed along a number of parallel paths to take advantage of different technical breakthroughs as they occurred, eliminating technologies that showed little promise. This approach explained why AFWL supported work on a variety of laser types, as well as projects on optics, beam diagnostic techniques, mission analysis, and conceptual design studies.[3]

In September 1967, AFWL outlined a program to demonstrate laser weapon feasibility and in early October 1968, was authorized to began building and testing a GDL. Since the laser field was in such a state of infancy, AFWL let GDL research contracts with two separate companies. In that same year, ARPA funded a Tri-Service Laser (TSL) that involved all three military services, but concentrated the laser research with AFWL. AFWL let its TSL contract in early 1969. Although the TSL was assembled at AFWL's Starfire Optical Range (SOR) beginning in April 1970, the device couldn't produce a good quality beam. To break through the TSL logjam, in December 1971 AFWL's leadership opted to accept the device as a "nonconformable item." AFWL formed an ad hoc team of in-house troubleshooters and within four months, the team produced a high-power beam of good quality. Commensurately, AFWL worked on an optical system. These mirrors would accept the laser beam and then align and steer it

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[3]   *Airborne Laser,* pp. 33-34; Interview with Lamberson, 12 Jan 1989; Interview, Duffner with Col David R. Jones, USAF, Retired, 19 Sept 1988; Interview, Duffner with Dr. Petras V. Avizonis, AFWL/ARTO, 16 Dec 1988; Rpt, n.a., "Advanced Development Plan" [hereafter cited as "Development Plan"], WLRE-67-133, Sept 1967, pp. 1-2.

to a field test telescope (FTT) that focused and pointed the beam to its target. AFWL let its contract to build the FTT in February 1969. In October of 1971, the FTT passed a critical milestone by successfully tracking a diagnostic aircraft at the SOR, and focusing a low power CO_2 laser beam on the aircraft – the first time a laser hit a target in flight.[4]

The next critical milestone required integrating the FTT and TSL components and testing them as a single system. AFWL first fired the TSL/FTT device at stationary targets downrange from the SOR, determining that the FTT could accurately focus and hold the beam and direct it to a desired target aimpoint. Then in December 1972, a wallet-sized target was mounted on a 30-foot rotoplane, which resembled a windmill, to rotate the target 360 degrees at 25 revolutions per second. The FTT pointed the laser beam and accurately hit the moving target for several seconds at over a mile away.[5]

Following the success of the integrated TSL/FTT device, some members of the ALL team thought that rather than going directly to installing and testing the device on an aircraft, a ground-based shootdown of an aerial target was the next logical step. Known as Project DELTA (Drone Experimental Laser Test and Assessment), the target was a 12-foot long, 248-pound Army drone flown at approximately 200 miles per hour near the Starfire Optical Range. To make the tests as realistic as possible, the drone's fuel tank resembled one used in an F-4 aircraft. On 13 November 1973, the DELTA beam disabled the drone long enough for it to lose control and crash, but caused only minor damage. The next

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[4] *Airborne Laser,* pp. 18-39; Interview with Lamberson, 12 Jan 1989; Interview with Avizonis, 16 Dec 1988; Interview, Duffner with Harry I. Axelrod, Hughes Aircraft Company, 27 Jan 1993; "Development Plan," pp. 1-2.

[5] *Airborne Laser,* pp. 23-37; Interview with Axelrod, 27 Jan 1993; Briefing chart, AFWL/ARTO, "TSL Milestones," 7 Sept 1972; Rpt, Col Robert W. Rowden, AFWL/CC, "AFWL Significant Events," 31 Dec 1972.

day, in a spectacular blaze of fire and smoke, the laser disabled drone tumbled 200 feet before hitting the ground. Project DELTA was a major milestone. For the first time a high-energy laser beam shot down a flying target and clearly demonstrated that all of the functions of an integrated system worked together.[6]

Several years before the proof of concepts in TSL, FTT, and DELTA were completed, a number of long-range laser planning and feasibility studies were already under way that supported the idea of putting a laser on a plane. In 1970, AFWL contracted for conceptual airborne testbed (ATB) design studies that recognized that system integration of all of the components inside an aircraft was a much greater problem than had been anticipated. AFWL decided to use a C-135 aircraft for the ATB, with a turret atop the plane housing an airborne pointing and tracking (APT) system so as not to limit the field of view in acquiring, tracking, and engaging aerial targets. AFWL acquired the testbed, an older but reliable and low-mileage NKC-135A aircraft (N for "nonreturnable" and K for "tanker"), in March 1972.[7]

The next progression was to conduct aerial proof-of-concept experiments, or cycles, on the ALL. Cycle I would show the APT could accurately track an aerial target. Cycle II would align a low-power beam with the APT and then direct the beam out of the turret on top of the aircraft to an aerial target. Cycle III, the most difficult part of the program, would combine a high-power beam with the APT to shoot down aerial targets.

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[6] *Airborne Laser,* pp. 39-42; Interview, Duffner with Richard V. Feaster, Colonel, USAF, Retired, 12 Jan 1989; Rpt, Col Richard V. Feaster, et al., "Project DELTA," AFWL-TR-74-250, Oct 1974, pp. 3-4, 9-10; Article, John G. Duffey and Darrell E. Spreen, "Project DELTA," *Journal of Defense Research, Series A: Strategic Warfare— High Energy Lasers,* vol. 4A, No. 1, May 1975, pp. 41-47.

[7] *Airborne Laser,* pp. 43-59, 77-80; Interview with Axelrod, 27 Jan 1993; Interview with Avizonis, 16 Dec 1988. For example of early airborne applications see Rpt, D. Green, et al., "Airborne Application Study," AFWL-TR-69-125, vols. I-IV, Oct 1969.

Cycle I work began in November 1970. AFWL's leadership deliberately planned to build the APT and modify the aircraft simultaneously so that both would be completed at the same time. A contractor built the APT, which had to be two-and-a-half times more precise than the FTT, in the summer of 1972 while another contractor modified the aircraft and created the ATB by March 1971. The lab worked with its contractors to insure the APT fit snugly, and installed the varied subsystems inside the craft, even while keeping the aircraft's weight under its maximum load. With assistance from its sister Air Force labs, AFWL designed and tested the APT turret and a zinc selenide window on the APT that protected its internal optics during flight.[8]

Lab scientists were concerned about the aerodynamic effects of placing a turret on top of the fuselage. Airstream movement around the APT could cause extreme buffeting that might inflict severe fuselage damage and destabilize the aircraft. The lab decided that a specially designed fairing would have to be installed around the turret. Wind tunnel tests proved that it would be impossible to fly the aircraft without fairings around the turret. The lab first put a mock turret with the fairing on the ATB, conducted a series of flight tests, and then installed the final APT version onto the aircraft. Finally, from May to November 1973, the airborne APT tracked various aircraft and air-to-air missiles at White Sands Missile Range (WSMR). At each stage, the lab adjusted the APT for vibrations and air turbulence. AFWL determined that the tracker functioned accurately, and thus Cycle I had met its milestone.[9]

Cycle II lasted from November 1973 to March 1976. AFWL used a low-power electric discharge laser (EDL) to safely align the laser beam inside the

[8]   *Airborne Laser,* pp. 85, 95-113, 129-142; Interview with Lamberson, 12 Jan 1989; Interview, Duffner with Dr. Raymond V. Wick, AFWL, 13 April 1990; Telecon, Duffner with Ernie Endes, Honeywell's Sperry Defense System Division, 30 March 1990.

[9]   *Ibid.*

interior of the aircraft into the APT. The EDL did not use dangerous laser fuels, and if its beam went off track, would do little damage to the aircraft interior. AFWL added systems to the ALL, aligned the mirrors in the APT, improved the APT so it would slew as smoothly as possible, and calculated the target aimpoint. The lab fired the laser from inside the parked ALL at ground targets or at aircraft in flight. Flight tests over White Sands Missile Range to track missiles and aircraft proved that an airborne laser could intercept an aerial target.[10]

What delayed completion of Cycle III were the continual engineering complications with integrating the equipment inside the ATB. A contractor subjected the ALL to major structural, mechanical, electrical, and safety modifications, and the aircraft was again certified for flightworthiness, all of which lasted until December 1977. For safety purposes, the lab constructed a test cell that essentially served as an identical mock-up of the NKC-135 and tested various systems there before installing them onboard the aircraft. These systems included a contractor-built fuel supply system (FSS), the Airborne Dynamic Alignment System (ADAS) beam director, the APT, and the GDL, all of which arrived and were tested separately and together between December 1974 and August 1980. Finally, in October 1980, AFWL assembled all of the various components aboard the ALL. In January 1981, the ALL team fired the high-power laser beam at a static target on the ground downrange from the aircraft – the first time all of the components of the laser system worked as one unified system to produce a beam that could be pointed to a target. Beginning in February 1981, the ALL attempted to track tow targets at WSMR and air-to-air missiles at the Naval Weapons Center Test Range in California.[11]

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[10] *Airborne Laser,* pp. 143-170; Rpt, Edward A. Duff, James E. Negro, and James F. Russell, "USAF Precision Pointing and Tracking Systems for High Energy Laser Applications—Test Results," AFWL-TR-74-285, Dec 1975, pp. 7-10; Article, Donald L. Lamberson, "Overview of the Air Force High Energy Laser Program," in *Second DOD High Energy Laser Conference Proceedings,* Nov 1976, pp. 31-42.

[11] *Airborne Laser,* pp. 171-253; Paper, John W. Dettmer and Demos T. Kyrazis, "Overview of the Airborne Laser Program," July 1979, pp. 379-396; Rpt, AFWL,

But numerous problems – especially the inability of the APT to track the missiles and the misalignment of the beam in the ADAS – spelled failure of the ALL to produce a kill. Then disaster struck as long-term water contamination damaged the beam steering mirrors, and replacing the entire mirror system caused a year's delay. AFWL then conducted tests in April 1983 at White Sands Missile Range and proved that the ALL's component systems were again fully integrated and capable of destroying a target.[12]

The ALL arrived at Edwards AFB on 15 May 1983 and prepared for its final test. It would be going up against the AIM-9B "Sidewinder" air-to-air missile, 111 inches in length, weighing 155 lbs, with a range of 2 miles at a speed of 2000 mph. The ALL first conducted a series of practice runs to test the acquisition and tracking systems against 19 live missiles. Then on 26 May 1983, the ALL completed the world's first successful airborne engagement of an aerial target when it destroyed an AIM-9B over the Naval Weapons Center Test Range at China Lake, California. The beam remained on the nose of the missile long enough (4.8 seconds) to heat up and damage the sensitive components of the guidance system, causing the missile to break lock. In follow-on tests, the ALL's powerful laser disabled four other AIM-9B missiles.[13]

The ALL team was now ready for its next challenge, disabling or destroying slow-moving drones that resembled cruise missiles. The BQM-34A drone was

"Airborne Laser Laboratory Cycle III Test Plan (Executive)," 31 Oct 1977, pp. 3-5, 93-94.

[12] *Airborne Laser,* pp. 248-278; Interview, Duffner with Harrison H. Schmitt, former U.S. Senator, 15 Jan 1993; News release, USAF/AFSC, "Laser Test," AFSC #81-12, 3 Feb 1981.

[13] *Airborne Laser,* pp. 279-296; Rpt, Raymond V. Wick, "Airborne Laser Laboratory Cycle III: Systems and Test Descriptions," AFWL-TR-86-01, vol. I, May 1988, p. 87; Article, n.a., "Airborne Laser Laboratory: 'Five for Five' in Sidewinder Tests," *Aerospace Daily,* 28 July 1983, p. 149.

larger than the AIM-9B at 23 feet in length, 3 feet in diameter with a wingspan of 13 feet, but flew at a slower 690 mph. Again, the ALL team conducted rehearsal tests prior to taking on the target. The results were the same. In September of 1983, the ALL's beam intercepted three Navy BQM-34A drones over the Pacific Ocean near Point Mugu, California. The beam burned through the third drone's flight control box, melted wires, and caused multiple circuit failures. As the electrical system failed, the drone went out of control, rolled 90 degrees to the right, and then crashed into the ocean. After almost 16 years and significant financial investment, AFWL's ALL team had accomplished its mission. [14]

The ALL was truly revolutionary because of the results it achieved. Proving for the first time that an airborne laser could intercept and disable aerial targets, the ALL ranks as the Wright Flyer of the laser world. This laboratory achievement marked an unparalleled technical milestone, clearly showing the potential for advancing high-energy lasers as a new class of defensive directed energy weapon systems. It served as the technological bridge from early laser and beam control demonstrations to the next generation Airborne Laser (ABL). [15]

Aside from the technical achievement, there were other significant "lessons learned." Due to the newness of laser technology, AFWL chose to invest in several research directions and let the most functional system win out, as well as developing different components concurrently in order to avoid losing time. The lab's confident leadership proved to be wizards of systems management, and kept a program with multiple component and subcomponent systems on track as they successfully convinced the Air Force brass to maintain their support in the face of numerous setbacks. The testament to their achievement was not only the

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[14] *Airborne Laser,* pp. 296-306; News release, USAF/AFSC, "Air Force/Navy ALL Test," AFSC #83-130, 29 Nov 1983.

[15] *Airborne Laser*, pp. 311-316.

successful shootdowns of 1983, but the current development of the Airborne Laser program today, which the Air Force Research Laboratory continues to support.[16]

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[16]   *Ibid;* Rpt, Lawrence Sher, "Lessons Learned from the Airborne Laser Laboratory," AFWL-TR-83-5, June 1983, pp. 54-56.

Aircraft Transparencies

In the fall of 1905, Orville and Wilbur Wright took their Wright Flyer to the fields of Huffman Prairie, today part of Wright-Patterson Air Force Base, to learn the art of practical flight. Among the circles and figure-eights the Wright Brothers flew that season, they continued to establish many "firsts" in aviation history. Wilber Wright reached one unanticipated milestone on 7 September. While fulfilling one of mankind's long-held dreams of literally chasing a flock of birds through the sky, Wilbur's plane hit one of the birds, marking the first ever bird strike on an aircraft. He landed safely, but the bird did not. It was not until seven years later that the first pilot died due to a bird strike. In that instance, a bird hit and became entangled in the control wires of a later model Wright aircraft flown by an Army pilot, resulting in a loss of control and a crash into the ocean. Until the end of World War II, bird strikes were considered relatively infrequent occurrences, rarely resulting in catastrophic damages. The major factor in that level of safety was the piston-engine driven propeller, which effectively prevented birds from hitting the engine itself or the glass canopy protecting the pilot. In addition, the relatively slow speeds afforded birds an opportunity for avoidance. Data shows that very few, if any, other fatal bird strikes were reported prior to 1955. After that point, turbine engine aircraft had come into widespread use, bringing with them higher speeds, vulnerable frontal areas, and more delicate exposed parts. The result was not only a greater incidence of bird strikes, but of serious and fatal collisions. Statistically, the most deadly of these hits occurred when the bird ran into the windshield or canopy, resulting in the disabling or death of the pilot.[1]

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[1] Website, Air Force Aviation Safety Division, "Bird Aircraft Strike Hazard homepage" [hereafter cited as "Bird Aircraft"], available on the internet at http://afsafety.af.mil/AFSC/Bash/home.html, as of 28 Nov 05; Thesis, Christine A. Tedrow, "Bird Strike Risk Assessment for the United States Air Force Airfields and Aircraft" (Virginia Polytechnic Institute and State University) Dec 98, pp. 1-2; Article, Jay C. Neubauer, "Why Birds Kill: Cross-Sectional Analysis of U.S. Air Force Bird Strike Data" [hereafter cited as "Why Birds Kill"], *Aviation, Space, and Environmental Medicine,* Apr 90, pp. 343, 345-346.

Early aircraft transparencies[2] were made of glass formed in small flat plates or in gently curved panels. The need for better visibility in combat and to contain pressurized cockpits prompted the introduction of plastics, both cast to a particular shape and stretched from a flat sheet over a mold. Plastic enabled the highly effective bubble canopies used in most fighter aircraft. During the 1950s and 1960s, a combination of strengthened glass panels and stretched acrylics were the most ubiquitous materials used for transparencies. These worked well as the jet engine brought the Air Force's propensity for higher and faster flight to its zenith. However, the tactical experience in Vietnam, particularly the impact of highly effective surface-to-air missiles, brought the Air Force literally back to earth. Survivability in that environment meant low-altitude, high-speed flight, bringing the fighter aircraft down into the realm of birds once again. Unfortunately, the tactical aircraft of the day, such as the F-4 Phantom, were not designed for that type of flight and did not have bird strike resistant transparencies. The result was both an increase in bird strike incidences and in pilot injuries for tactical jets. The problem grew worse during the 1970s, as the number of strikes rose steadily.[3]

Though bird strikes were encountered by the other military services and domestic aircraft, as well as worldwide, the problem was felt most acutely by the Air Force. The Air Force Flight Dynamics Laboratory (FDL) responded to this problem in a systematic way beginning in the early 1970s. That effort gathered steam through the 1980s and 1990s. The FDL's Vehicle Subsystems Division looked at many existing materials to see how they might apply that technology to

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[2] The term "transparency" means the totality of clear material surrounding the cockpit, while "canopy" specifically refers to the clear panel covering the top and sides of the pilot, and "windshield" specifies that in front of the pilot. However, these terms have become loosely interchangeable, particularly after the advent of single-piece transparencies.

[3] Article, James H. Brahney, "Windshields: more than glass and plastics" [hereafter cited as "Windshields"], *Aerospace Engineering*, vol. 6 (Dec 86), pp. 28, 31.

improve the safety of Air Force aircraft. Resistance to bird strikes was only one of the criteria, however. The researchers also considered visibility, cost, maintainability, durability, and other factors. The result was a series of programs to both improve the general state-of-the-art and to improve the transparencies of existing aircraft. To address technological deficiencies, the FDL had to update the analysis and testing capabilities relevant to windscreens. The so-called "chicken gun," or bird impact facility was devised as a repeatable method for testing the damage done by bird carcasses fired at aircraft components. Both Wright-Patterson and the Arnold Engineering Development Center (AEDC) operated such a facility from 1972 on, but the University of Dayton Research Institute (UDRI) took over the former's gun five years later. To complement that seemingly low-tech, traditional test facility, the FDL devised a computer program dubbed "Materially and Geometrically Nonlinear Analysis" (MAGNA) for the simulation of the dynamic structural response of transparencies to bird impact. Other computerized tools for aerothermodynamic and optical analysis followed to support the pioneering work at a lower cost than trial-and-error physical testing.[4]

The improvement in transparencies that occurred from the mid-1970s through today is the result of work done in three interrelated areas: materials, structures, and design. The Flight Dynamics Lab's contributions to materials came out of its expertise in composite materials, an area in which it was at the forefront for aircraft applications. The first real alternatives to acrylics and glass were polycarbonates. This material was not new, but it had taken until the late 1960s to improve it to optical quality, an effort pushed by NASA for its space suit helmets. Polycarbonates demonstrated excellent impact resistance, but were susceptible to environmental effects, such as clouding in sunlight, and were prone to scratching. Those characteristics meant that polycarbonates were best

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[4] "Windshields," p. 31; Book, ASC/HO, *Splendid Vision, Unswerving Purpose* [hereafter cited as *Splendid Vision*], (WPAFB, OH: ASC History Office) 2002, p. 328; Book, James J. St. Peter, *The Flight Dynamics Laboratory: Evolution of an Engineering Miracle* (WPAFB, OH: Flight Dynamics Laboratory, Oct 88), pp. 93-94.

used as a ply in a laminate structure canopy, surrounded by coatings and other material layers. The F-15 and F-16, both of which came into production during the 1970s, were designed using polycarbonate canopies, partly because of impact resistance and partly because of its excellent temperature characteristics. The FDL paired its research into new transparent materials, such as structural thermoplastics, elastomeric interlayers, and coatings, with revisions to the underlying canopy structure. The result was a new class of high-energy, bird impact resistant laminated plastic windshields and canopies applicable to the next generation of aircraft coming out, including the F-15 and F-16.[5]

In the early 1980s, the Flight Dynamics Lab began several programs to retrofit legacy aircraft with improved transparencies. The timing was prompted by alarming statistics, such as the fact that nearly half of the 68 reported bird-canopy collisions for the F-4 resulted in cockpit penetration, with 12 injuries and one death. The first such effort was the F-111, which was designed for low-altitude, high-speed flight, but its canopy used the technology of the 1960s, when the fighter-bomber was designed. It initially used two plies of glass with a layer of silicone separating them. This material and its mission mode made it particularly susceptible to bird damage. The redesign effort of the late 1970s made it the first legacy aircraft to take advantage of acrylic-faced polycarbonates. A similar effort went into improving the transparency used on the T-38 training aircraft, which was second only to the A-10 in numbers of bird strikes sustained. Perhaps the most famous incident with the T-38 involved Air Force test pilot and NASA astronaut Ted Freeman, who struck a large goose with his jet near Houston in 1964. He survived the impact, but pieces of the shattered canopy entered his engines, causing both to flame out. The loss of power and low altitude led to Freeman's unsuccessful ejection and death. The FDL program paved the way for its work on subsequent aircraft. In 1982, several Air Force

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[5] "Windshields," pp. 31-33; Manuscript, Dr. James F. Aldridge, ASC/HO, "USAF Research and Development" [hereafter cited as "R&D"], 1997, pp. 59-60.

major commands approached the Flight Dynamics Laboratory with their concerns over the F-4's vulnerability to bird strikes, starting a concerted effort to study the bird impact problem and redesign the transparency. With the assistance of AEDC, UDRI, and multiple vendors, the FDL devised new panels, included a single-piece windshield made of multi-ply acrylic/polycarbonate that nearly doubled the impact resistance of the entire system. Similar programs were enacted for other aircraft, such as the A-7, T-37, and A-10. Like the F-111, the B-1 bomber was designed for a low-altitude mission, but its advanced canopy design of glass, polycarbonate, and coatings were capable of significantly higher impact resistance.[6]

The F-16's was the first fighter to make use of modern transparency materials for a one-piece "bubble" canopy. The complex shape was made from a laminate of polycarbonate and acrylic. Since then, the Flight Dynamics Lab has worked on improving single-piece canopy designs using a variety of materials and manufacturing techniques. Starting in the mid-1980s, the lab demonstrated that transparencies could be formed in a single process directly from plastic resins, rather than being formed from flat sheets and modified. The FDL program "proved the feasibility of direct forming of large transparencies from plastic materials, with the resulting part having superior optical clarity, repeatability, and impact toughness." The key to its success was the use of low-pressure injection molding. The first generation transparencies produced using

[6] "Windshields," pp. 31, 34; Paper, Lt Robert Simmons and G. J. Stenger, "Bird Impact Evaluation of the F/RF-4 Transparency System," in *Proceedings of the Bird Strike Committee Europe, 18th Meeting,* Denmark Civil Aviation Administration, 26-30 Copenhagen, Denmark, May 1986, pp. 191-192, 195-196; History, AFSC/HO, "History of the Aeronautical Systems Division October 1982-December 1983 (Fiscal and Calendar Year 1983) Part II: The Air Force Wright Aeronautical Laboratories," Oct 82-Dec 83, pp. 32-33; "Why Birds Kill," pp. 343, 345; Paper, William A. Miller, "Polycarbonate Aircraft Transparencies," in *Proceedings of the Sixth National SAMPE Technical Conference,* vol. 6, Society for the Advancement of Material and Process Engineering, Dayton, Ohio, 8-10 October 1974, pp. 218-228.

this technology weighed 20 percent less and showed an 80-90 percent cost savings over the previous method. Other benefits included faster change-out time, a two orders-of-magnitude reduction in parts, and lower cost of ownership. Refining the technology to meet all of the operational requirements proved difficult, however. The FDL and its successor, the Air Force Research Laboratory's Air Vehicles Directorate (AFRL/VA) continued to pursue injection molded frameless technology into the 1990s and 21st century through its Next Generation Transparency (NGT) program. The NGT work looked to replace the canopy of the F-15 and T-38 and to transition the technology to the newest aircraft, the F-22 and F-35.[7]

The progress made in aircraft transparencies materials, design, and structures undoubtedly saved million of dollars in damage prevention and the priceless lives of skilled pilots. Results speak for themselves: compared with the F-4's windshield penetration statistics cited above, from 1985-2004, only 67 of 8,867 such strikes had the same result across the entire Air Force fleet – less than 1 percent. As the focal point of the Air Force's research in this technology, the Air Vehicles Directorate and its predecessors were responsible for devising, developing, and implementing many of the novel concepts employed over the past three decades.[8]

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[7] "R&D," pp. 65-66; *Splendid Vision*, p. 328; Rpt, n.a., "Next Generation Transparency Study Parts I & II Final Report," WL-TR-97-3108, May 97. Brfg, Mike Gran, AFRL/VASM, "Next Generation Transparency Program Baseline," 5 Dec 02.

[8] "Bird Aircraft."

Altitude Protection – Pressured Breathing

Research by Capt. Harry G. Armstrong and Dr. J. William Heim of the Aero Medical Research Unit (AMRU) in the late 1930s revealed that above 33,000 feet, with aviators breathing 100% oxygen, arterial oxygen saturation markedly decreased, falling to 88% saturation at 40,000 ft. This situation forced them to conclude that "Flights at 25,000 feet must be considered definitely hazardous, and 30,000 feet should be the absolute allowable flying in any except the most unusual circumstances. In no case should anyone be allowed to fly above 40,000 feet."[1]

As World War II began, however, Army Air Forces officials foresaw that aircrews would need to fly at high altitudes without recourse to a pressurized cabin or pressure suits. Realizing that flying above 41,000 feet could be done only if blood–oxygen saturation could be maintained above 85%, Captain Adolph Pharo Gagge of the AMRU (shortly to be renamed the Aero Medical Laboratory) in late 1941 and the spring of 1942 conducted an experimental program to determine if increasing the oxygen pressure in the lungs throughout the respiratory cycle by 15 to 25 mm of Hg could increase the oxygen ceiling for continued operation by several thousand feet. Pressured breathing, which had already been used as a therapeutic measure for clinical treatment of bronchitis, pneumonia, asthma, and other forms of lung infection, was in effect, breathing in reverse, that is, the active and passive phases of respiration were reversed. A crewperson, rather than actively inhaling oxygen as one normally did at lower altitudes, instead had air forced into his/her lungs by pressure from an oxygen tank. That person, or the pressure suit he or she was wearing, physically forced the air out; otherwise he or she passed out.[2]

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[1]   Note, n.a., "Altitude Protection – Pressure Breathing" [hereafter cited as "Pressure Breathing"], n.d.

[2]   Article, Lt. Col. A. P. Gagge, Capt. S. C. Allen, and 1st Lt. J. P. Marbarger, Aero Medical Laboratory, Wright Field, "Pressure Breathing," *Journal of Aviation Medicine,*

Born in Columbus, Ohio, on 11 January 1908, Gagge earned a Ph.D. degree in physics from Yale University in 1933. He then worked at the John B. Pierce Laboratory, an independent research facility affiliated with Yale that was dedicated to exploring the impact of the environment on human health. It was here that he began a lifelong study of the reaction of the human body and its temperature regulation to variations in atmospheric conditions, radiation, convection, air movement, and clothing. In 1941 Gagge joined AMRU's Biophysics Branch, which he later headed before serving as AML's director of research and acting chief. From 1950 to 1955 he headed the Human Factors Division of the USAF Research and Development Headquarters in Washington, D.C. During the next five years, as he advanced to colonel, he worked in the USAF Office of Scientific Research, serving as its commander at the end of this period. From 1960 to 1963 he was manager of the Cloud Physics, Weather Modification, and Joint Services Electronics programs in the Department of Defense's Advanced Research Projects Agency. After retiring from the Air Force in 1963, he successively became associate professor of physiology and epidemiology (1963-1969), professor of epidemiology (environmental physiology) (1969-1976), and professor emeritus (1976-1993) at Yale University's School of Medicine. Before his death, in Branford, Conn., on 13 February 1993, he authored over 137 publications.[3]

On 12 December 1941, Gagge successfully used an experimental breathing circuit of his own design in AMRU's hypobaric chamber to a simulated altitude of 43,000 feet. He wore a mouthpiece (similar to that in a standard metabolism apparatus) that was fitted between his teeth and lips and held to his face by a

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vol. 16, Feb 45, pp. 2-8. This paper was presented at the 16th Annual Meeting of the Aero Medical Association of the United States, St. Louis, MO, on 5 Sep 44.

[3] Article, Henning E. Von Gierke, "A. Pharo Gagge 1908-1993," *Memorial Tributes: National Academy of Engineering,* vol. 7 (Washington: National Academy Press), 1994, pp. 68-72, available on the Internet at http://www.nap.edu/books/0309051460/html/68.html on 15 Nov 05.

Canadian-type oro-nasal mask and straps. Rubber sponges placed between each side of the nose and the mask effectively sealed the oxygen leaks through the nose. Gagge breathed from a closed circuit consisting of a motor blower and a sodaline container to absorb the exhaled carbon dioxide. A large rubber spirometer took up the tidal air of respiration. As carbon-dioxide absorption lowered the height of the respiration bellows, a cam attached to the bellows actuated a microswitch that caused the solenoid valve to the oxygen supply to open. The apparatus allowed the oxygen used by Gagge's body in each breath to be continuously and automatically replaced into the respiration system. Weighting the top of the rubber bellows spirometer permitted variation of the pressure in the oxygen system. Under these conditions, the system maintained an arterial saturation of 84%, compared with a control of 75% at ambient pressure.[4]

Colleagues and contractors soon began simplifying the equipment used in Gagge's experiment. In June 1942 the J. H. Emerson Company of Cambridge, Mass., developed a spring-weighted, initial-pressure breathing regulator, standardized as the A-12, that was especially designed for pressure breathing. The following summer researchers developed a pneumatic vest to ease the respiratory effort, but they subsequently discarded it because its impracticability outweighed the slight assistance given. In October 1942 Gagge's colleague Capt. Francis Randall designed a sealed pressure-demand face mask based on anthropometric facial measurements. Made from plaster molds and latex, these A-13 masks were subsequently manufactured by the Mine Safety Appliances Corporation (MSAC) of Pittsburgh, Pennsylvania. In January 1943 B. B. Holmes of the Pioneer Instrument Division of Bendix Aviation Corporation in Bendix, N.J., designed an improved pressure demand regulator subsequently standardized as the A-17. To prevent failure of the mask due to freezing, rebreathing was not

[4]   Book, Mae Mills Link and Hubert A. Coleman, *Medical Support of the Army Air Forces in World War II* [hereafter cited as *Medical Support*], (Washington: Office of the Surgeon General, USAF) 1955, pp. 265-266.

allowed to occur through any part of the inspiratory passages to the mask bowl, and the expiratory passage needed to be as short and direct to the outside as possible. A key invention to cope with this problem was a compensated exhalation valve conceived by William A. Wildhack of the National Bureau of Standards during a visit to Wright Field in the spring of 1943. The valve loaded automatically with an exhalation resistance slightly higher than the supply pressure from the regulator. The oxygen inlets to the mask contained two cheek check valves that closed during exhalation when the mask pressure was higher than the supply pressure. The Linde Oxygen Company subsequently developed a practical design for this valve.[5]

Lt. Col. (Dr.) W. Randolph Lovelace, with Boeing pilot A. C. Reed and co-pilot J. A. Frazer at the controls of a specially modified B-17E, made the first aircraft flight with pressure-breathing equipment (Randall's A-13 pressure-demand breathing mask and an Emerson A-12 regulator) to an altitude of 42,000 feet, in November 1942. Five months later, in April 1943, Lockheed test pilot Joe Towle used the mask with a Holmes A-17 regulator in a P-38 flight up to an altitude of 44,980 feet. After photographic reconnaissance groups became aware of the possibility of using pressure-breathing equipment in high-altitude missions, the Army Air Forces (AAF) began training such squadrons with the equipment at Wright Field, beginning with the 28th Photo Squadron from 26 October to 6 November 1943. Later in November the AAF officially adopted the equipment for photo reconnaissance use and authorized purchase of 4,000 sets of equipment, which consisted of the MSAC A-13 mask fitted with compensated exhalation valves and Arotype A-14 pressure-demand regulators. The early sets of the A-14 used the Holmes A-17 chest-mounted regulator with the Linde mask valve. The 14th Photo Reconnaissance Squadron, using Spitfires rather than P-38s, conducted the first operational mission with the equipment in February 1944, and used them for the first time over Berlin two months later. Pilots of new

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[5] "Pressure Breathing," p. 7; *Medical Support,* pp. 266-267.

F-5 and F-13 aircraft were equipped and trained with the equipment and made use of them in high-altitude flights over Tokyo in November 1944. Air Force and Navy pilots used the mask and improved variants, which ultimately allowed them to reach altitudes up to 60,000 feet, well into the 1960s.[6]

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[6]   *Medical Support*, p. 267.

Carbon-Carbon Composites

The Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/ML) and its predecessors have been the service's center for materials research since 1917. Its early work in synthetic materials prior to World War II led to the development of composite materials, or those made of fibers bound in a resinous matrix. What was then the Materials Laboratory at Wright Field began its first significant research into composites during the Second World War. During those years, it initiated much new research activity, especially for advanced aluminum alloys, new plastics, synthetic fibers, and synthetic rubber. These latter efforts were only one component of work done by all the belligerent countries to find substitutes for critical war materials. The head of the Army Air Force, Gen Henry H. "Hap" Arnold, gave the Materials Lab specific direction to explore the use of composite materials for aircraft construction. This was not a totally new area for it; it had investigated the use of fiberglass-reinforced plastics since the late 1930s. As a result of Arnold's direction, Materials and the other labs at Wright Field established a cooperative task force to develop and find application for composites. The task force canvassed industry for expertise and immediately began work on improving the materials and designing the first structures. The first of these applications were aircraft radomes made of fiberglass-reinforced polyester. Other early demonstrations included a glass-fiber-reinforced plastic for the Vultee BT-15 trainer aircraft's aft fuselage, which was the "first major fiber reinforced plastic structural component of an aircraft to be developed and flight tested."[1]

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[1]   Manuscript, Dr. James F. Aldridge, ASC/HO, "USAF Research and Development" [hereafter cited as "R&D"], 1997, pp. 17-19; Paper, n.a. [AFRL/ML], "A Condensed History of the Air Force Materials Laboratory/Directorate" [hereafter cited as "History Materials Lab"], n.d., pp. 6-9.

Post-war work continued with research in basic materials and applications of materials such as glass-fiber reinforced composites. This was done on a rather limited basis until the early 1960s when the Air Force prioritized advanced composites as one of its promising new technologies for future aircraft through its *Project Forecast* study. In 1963, Air Force Systems Command commander Gen Bernard Schriever commissioned *Project Forecast* to analyze the Air Force's force structure for the next decade and find technologies that could, if properly pursued, substantially contribute to that future. The Materials Lab (renamed Materials Central from 1959-1963, and the Air Force Materials Lab, AFML, August 1963) made a concerted effort to bring budding composite technologies to the *Project Forecast* team's attention, eventually winning praise for its work in the field and inclusion in the final recommendations. As a result, the lab created an Advanced Filaments and Composites Division. This entity focused initially upon increasing the number of advanced composites applications and then moved aggressively into establishing a sturdy foundation for composites analysis. Its work led to the formulation of equations and theories that would be used in textbooks and computer codes.[2]

The Materials Lab felt confident of the potential of composites because of recent breakthroughs in the field prior to *Project Forecast*. Carbon-carbon composites (CCC), or those composed of fibrous carbon reinforcements in a carbonaceous or graphite matrix, were among these innovations. The discovery of CCCs began at the intersection of chance and a prepared observer. In 1958, a lab technician at Chance-Vought Aircraft's Astronautics Division (Later, Ling-Temco-Vought, or LTV) experimented with burning an oxide fiber-reinforced phenolic (plastic) composite, inadvertently covering it during the pyrolyzing (burning) process, resulting in a porous composite – composed of oxide fiber in a carbon matrix – with high impact resistance and strength. His supervisor showed the material to Materials Lab scientist Donald L. Schmidt, and together they

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[2]   "History Materials Lab," pp. 19-20.

recognized that the substitution of carbonaceous fiber would greatly raise the temperature limitations of the material. Schmidt and others began "an evening-hour, government funded laboratory research project" to explore a variety of carbon fibers because of the materials' properties of high thermal stability, strength and stiffness, dimensional stability, thermal conductivity, and lubricity. They were not the only ones, however. The tobacco industry did similar work to produce improved carbon filters for cigarettes and, more importantly, the Union Carbide Corporation was developing a graphite fiber based on rayon, which it soon began to develop for commercial applications. That company patented a process for combining graphitized woven and non-woven fibers into an early form of carbon fiber. Much work remained to be done, both to improve the availability of such fibers and to create a suitable carbon matrix.[3]

In 1960, the Materials Central felt "it was apparent that all of the necessary carbonaceous constituents would soon be available, and a government-funded developmental program would be desirable to explore various composite types, processing methods, and materials properties." Under Schmidt's direction, the Lab funded such a contract with Chance Vought. The initial work started in 1961 and used fibrous oxides for study, at least until the Union Carbide graphite fabric became available. After that point, the succeeding research used all carbonaceous materials, making it the first known "'dedicated' CCC material developmental program." Using in-house research, Materials Central studied the properties of ablative plastics used for missile nosecone reentry protection (and by the Mercury, Gemini, and Apollo spacecraft), and recognized that the charred material left on the surface of such heat shields had beneficial properties. These developments combined the technologies of the graphite industry with those of the organic matrix composite industry to create the best balance of properties in carbon-carbon composites. Materials Central pressed further advances in CCCs

[3]   Rpt, Donald L. Schmidt, University of Dayton Research Institute, "Carbon-Carbon Composites (CCC) – A Historical Perspective" [hereafter cited as "CCC"], WL-TR-96-4107, Sep 96, pp. 24-25; "R&D," p. 12.

through its Advanced Development Program on Graphites. This program improved both carbon matrices and fibers, as well as the processes for manufacturing improved components.[4]

During the 1960s, the Materials Central/Lab contributed to the advancement of all aspects of carbon-carbon composites, including its application to aerospace structures. In 1962, it developed a process of chemical vapor deposition of pyrolytic graphite as a means to densify carbon-carbon. It also fabricated the first generation of oxidation-resistant CCCs, using 2-D (that is, reinforced in a single plane) graphite fiber and phenolic resin char with borate, oxide, and silicate particulates. By the following year, the lab was scaling up silicon carbide-coated CCCs, which were later used on the space shuttle orbiter's nosecap and wing leading edges. The lab tested such materials in-house using arcjets for the simulation of re-entry conditions. In 1963, the Air Force Rocket Propulsion Laboratory (now AFRL/PRS) and the AFML conducted the first simulated rocket tests using carbon-carbon nozzles in both solid motors and liquid engines. Several major breakthroughs occurred in 1965. That year, the Lab developed the use of liquid pitch for a more graphitizable and higher density matrix, made the first use of chemical vapor deposition and chemical vapor infiltration techniques, and helped Union Carbide develop the first hot-stretched, rayon-based graphite yarn reinforcement fibers for high strength and high modulus of elasticity – the first "true" structural carbon reinforcement.[5]

During the 1960s, carbon-carbon composites researchers took that material from laboratory curiosity to the establishment of the basic concepts that persisted in the field in the decades to come. Work done during the 1970s focused on developing variants for specific system's needs, improving the perform and matrix densification processes, developing other composite configurations,

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[4]   "CCC," pp. 24-26.

[5]   "R&D," pp. 12-13; "CCC," pp. 33, 36

scaling up CCC sizes for prototype evaluations, generating property data, and demonstrating the utility of CCCs in various test and service environments. The Air Force's program proceeded vigorously to achieve a "lasting solution to the strategic missile reentry nosetip problem," that is, high ablation rates, poor nosetip shape stability during reentry, and unpredictable performance. A key AFML researcher wrote that, in the lab, "creativity was at its zenith." Its philosophy was to create a wide variety of new materials, study their properties, identify their key features, and tailor the products to specific applications. The result was a wide catalog of composite materials "created before a recognizable need existed for them," but that paid off in the future. The missile nosecone work expanded by the late 1970s to include an all-weather-capability. Private industry and other countries made significant contributions to the state of the art and to applications such as aircraft brake pads, and car brake rotors and clutch plates.[6]

The 1980s saw a major shift from basic research in carbon-carbon composites to "a more systems applications orientation," due to a fundamental change in how the U.S. defense establishment approached materiel development and a general decline in research activities in most relevant organizations. Some of these applications studied by the AFML included disc blade assemblies and combustors for turbine engines, space survivable structures, missile heat shields, and rocket nozzles. While applications of CCCs spread, major new innovations were limited to the development of a 5-D material (an additionally reinforced 3-D composite), and a rapid densification process invented in France and eventually licensed to the U.S. for defense applications. The use of CCCs for spacecraft structures was a major focus of the 1990s, both for use in structural members and for their value as a protective layer.[7]

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6   "CCC," pp. 73-76; "R&D," pp. 12-14.

7   "CCC," pp. 77-78; "R&D," pp. 14-16.

The AFRL Materials and Manufacturing Directorate and its predecessors have been involved with every step of carbon-carbon composites development since the precursor research of the late-1950s to the modern improvement of manufacturing techniques. In concert with the other AFRL directorates, such as Air Vehicles for structural applications and Propulsion for jet engine and rocket engine components, AFRL/ML has been a critical center of CCC research for nearly a half century. The national and international partnerships of government labs, academia, and private industry worked to improve this composite technology such that it is the material of choice for myriad applications, from extremely high temperature environments to those requiring low weight and high strength.[8]

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[8] "R&D," p. 11.

Chemical Oxygen Iodine Laser

After years of research and financial investment, in late 1977, three Air Force officers and an Air Force civilian scientist at the Air Force Weapons Laboratory (AFWL) invented and patented the Chemical Oxygen Iodine Laser or COIL. The laser had been invented in 1960, and very quickly, the Department of Defense recognized its potential as a military weapon. Indeed, at the time of COIL's invention, AFWL was already pursuing the CO_2 gas dynamic laser for its Airborne Laser Laboratory (ALL) experiment. But establishing an operational airborne laser weapon system required developing a laser with far better characteristics than the CO_2 device. COIL proved to be that laser, with advances continuing to improve its use aboard the current Airborne Laser (ABL) as well as commercial applications.

A laser, or *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation, is the most concentrated and powerful form of light known. For "lasing" to occur, three conditions must be met. First, some type of substance (gas, liquid, or solid) is needed to produce a beam. Second, an intense energy source (a pulsed-discharge lamp, a chemical reaction, or electricity) is required to excite and alter the condition of the selected material. And third, a resonator with mirrors at each end is required to extract the precise optical energy in the form of a beam. But lasers are notoriously inefficient, taking an enormous amount of input energy to produce a small amount of laser light. Not all of the input energy is converted to laser light. A large portion of the energy remains as heat, resulting in major cooling problems for the laser to operate efficiently. However, as potential weapon systems, lasers offer distinct advantages. Lasers travel over long distances at the speed of light. Optical mirror systems can focus the laser beam to deliver large amounts of energy to a very small area. Additionally, a

concentrated laser beam minimizes collateral damage to nearby structures and greatly reduces the potential for civilian casualties.[1]

Dr. Theodore Maiman, senior staff scientist at Hughes Aircraft Company's Research Laboratory, generated the world's first laser beam on 15 May 1960. The Department of Defense's Advanced Research Projects Agency (ARPA) quickly recognized the potential of using lasers on the battlefield, and funded a laser research program at the Air Force Special Weapons Center (AFSWC) in February 1962. ARPA's early investments in advancing laser technology at AFSWC and elsewhere resulted in several high-power laser systems, including the hydrogen fluoride (HF) and deuterium fluoride (DF) lasers, and the CO_2 gas dynamic laser, which AFSWC and its descendent, the Air Force Weapons Laboratory, and their contractors were pursuing. Although these various lasers worked well, they lased in relatively long wavelengths, requiring large optics and enormous infrastructure to store the energy necessary to enable them to operate. While AFWL developed the CO_2 GDL device for use in the ALL, it continued its laser research in several directions in the hopes of finding a more efficient, shorter wavelength laser with significant weight savings, important if the device went aloft.[2]

In the mid-1960s, researchers at the University of California, Berkeley, demonstrated the first successful chemical laser and the first iodine laser. Chemical lasers rely on chemical reactions to excite the molecules to create a laser beam. Operated at the short wavelength of 1.315 microns (a micron is

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[1]   Book, Robert W. Duffner, *Airborne Laser: Bullets of Light* [hereafter cited as *Airborne Laser*], (New York: Plenum Press), 1997, pp. 6-12.

[2]   *Airborne Laser*, pp.13-18; Article, Robert W. Duffner, Robert R. Butts, J. Douglas Beason, and Ronald R. Fogleman, "Directed Energy: The Wave of the Future" [hereafter cited as "Directed Energy"], in Book, *The Limitless Sky: Air Force Science and Technology Contributions to the Nation* (Washington, D.C: Air Force History and Museums Program), 2004, p.229.

equivalent to a millionth of a meter), Berkeley's low-power iodine laser only operated in short, single pulses. About the same time, the Air Force introduced extremely high-flying reconnaissance aircraft such as the SR-71 into the operational force structure. These aircraft flew in the stratosphere, and little was known about the air's chemical properties at that height. Consequently, there were concerns about the possibility of the effects of air pollution and corrosion on high-flyers.[3]

In 1965 the Air Force Office of Scientific Research (AFOSR) awarded a contract to researchers at the University of British Columbia to study the reactions of a particular chemical state of the oxygen molecule, called singlet delta oxygen, which was present in the upper atmosphere. Those researchers noted a strange chemiluminescence when mixing singlet delta oxygen and iodine. Soon after, other researchers noted the emission of 1.315 micron light emitting from the iodine atom and published a series of landmark papers that detailed the dissociation or break up of molecular iodine (I_2) by using the excited state of oxygen, singlet delta oxygen, and, thus, discovered a chemical excitation mechanism of the iodine atom. These academic researchers suggested that iodine could be altered or inverted if enough singlet delta oxygen could be produced – the laser's central problem.[4]

Those academicians' publications in 1971 provided the initial impetus for researchers at the Air Force Weapons Laboratory. AFWL scientists realized the potential of the iodine laser for weapon applications. Specifically, its short

[3]   Paper, William E. McDermott, "A History of the Oxygen Iodine Chemical Laser" [hereafter cited as "A History"], n.d., p.1; "Directed Energy," pp. 229-230; Paper, Glen P. Perram, AFIT, "Chemical Lasers" [hereafter cited as "Chemical Lasers"], n.d.

[4]   "A History," pp. 1-3; Article, William E. McDermott, "Historical Perspective of COIL" [hereafter cited as "Historical Perspective"], in Rpt, Steven J. Davis and Michael C. Heaven, eds., "Gas and Chemical Lasers and Intensive Beam Applications III, SPIE Proceedings," vol. 4631, 2002, p.1.

wavelength would allow the use of smaller optics and lighter supporting infrastructure, and it was not readily absorbed into the atmosphere. If it could be invented, a high-power, continuous-beam iodine laser would solve most of the problems associated with other high-power laser systems.[5]

In 1973, Dr. Alan McKnight began working on the oxygen iodine laser at AFWL. McKnight initially tried to define the kinetic rate constants involved in the production of inverted or altered iodine in order to computationally model an oxygen iodine laser. He also sought to locate a source to generate the critical singlet delta oxygen by unsuccessfully microwaving excited oxygen. In 1973, McKnight approached Major Bill McDermott, a PhD chemist with an interest in chemical lasers, then stationed at the Frank J. Seiler Research Laboratory—a basic research lab run by AFOSR at the USAF Academy. McDermott enlisted the assistance of other Seiler Lab researchers to work on the singlet delta oxygen production problem, and AFOSR provided incipient funding. McDermott became convinced that a liquid phase reaction between chlorine and basic hydrogen peroxide could generate sufficient amounts of singlet delta oxygen needed for lasing. The Seiler lab's successes convinced AFOSR and AFWL to continue their support of this growing effort.[6]

Major McDermott transferred to AFWL in 1977, about the same time as Dr. McKnight's departure. He worked with Major Ron Bousek, who ran the oxygen iodine chemical laser program at the laboratory. New arrival Dr. Dave Benard, while visiting the AFWL contractor selected to develop the singlet delta oxygen generator, determined that the contractor had established an iodine inversion. This discovery squelched threats to shut down the program, and AFWL received the generator. After briefly heading down what was the wrong path, the team reoriented itself by re-examining earlier work done by academic scientists as well

5   "A History," p. 4; "Historical Perspective," p. 2.

6   "A History," pp. 4-16; "Historical Perspective," pp. 2-4.

as earlier work done at the Academy. AFWL's Captain Nick Pchelkin continued to improve on McDermott's generator design, significantly increasing the amount of singlet delta oxygen needed to create a lasing action, while Benard prepared detectors to record the lasing. AFWL's machine shop, a glass blower, and several Air Force enlisted technicians supported their work. Finally, on 30 November 1977, a small spike in light intensity was observed. It was possible that lasing had occurred, but the next day when the experimental team realigned the mirrors, lasing occurred every time the team activated the fledgling laser.[7]

The COIL laser consisted of four basic parts. First, a generator produced the excited singlet delta oxygen, resulting from a chemical reaction between chlorine gas and basic hydrogen peroxide. Second, a trap removed undesirable chlorine, oxygen, and water vapor that interfered with the laser's gas kinetics. Third, a spray bar or nozzle injected iodine into the oxygen flow, and the excited oxygen dissociated the iodine and transferred energy. Finally, an optical resonator— mirrors at the ends of a cavity—extracted energy from the altered iodine to produce a laser beam.[8]

With this exciting advance, the world's first chemical oxygen iodine laser had been invented, yielding a power output of only 4 milliwatts, a mere four thousandths of a watt. Unlike the pulsed iodine laser invented a decade before, AFWL's proof of concept device was a continuous wave or CW laser and now the advantages of CW lasers could be exploited using chemical fuels. Majors McDermott and Bousek, Captain Pchelkin, and Dr. Benard, all of whom were Air

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[7] "A History," pp. 17-25; "Historical Perspective," pp. 4-5; Interview, Dr. Robert W. Duffner, AFRL/VSIH, with Nicholas Pchelkin, AFRL/DEOS, 24 Aug 1999.

[8] "Chemical Lasers;" History, AFWL/HO, "History of the Air Force Weapons Laboratory, 1 October 1984—30 September 1986" [hereafter cited as "History-AFWL"], vol. 1, 1987, p. 246; History, PL/HO, "Close-Out History of the Phillips Laboratory, 1 October 1996—30 October 1997," vol. I, 1998, p. 513.

Force personnel, authored the Air Force's patent on COIL awarded in 1981. Once AFWL proved that COIL worked, lab commanders and directors generously shepherded the COIL program along with funding, while Chief of Staff General Lew Allen, himself a former AFWL scientist, supported COIL research.[9]

A race commenced to dramatically increase the power of the subsonic laser. A second COIL device failed to withstand the required changes and did not lase, but in an almost apocryphal event, Capt Pchelkin and Dr. Benard had already designed the successful COIL III device on the back of a placemat in a local restaurant. By 28 July 1978, less than a year after achieving "first light," the power jumped to 100 watts in this new version of COIL, an increase of nearly 100,000 times. This effort paid high dividends, as year after year COIL reached record-power levels. By 1982, COIL IV incorporated significant advances and had produced over 4 kilowatts of power. This effort was overtaken in June 1984 when Dr. Gordon Hager and other AFWL scientists created the first supersonic COIL device or RECOIL with a power output of ~2 kilowatts, and a second device quickly reached over 4 kilowatts.[10]

Supersonic COIL devices, using mixing nozzles that move gases at supersonic speeds through the resonator cavity, were vastly improved over the subsonic COILs (I through IV). Supersonic devices reduced the size of the laser, reduced the cavity operating temperature and reduced water vapor to increase efficiency, and improved the beam quality, while improving the oxygen generators provided greater energy output. Most importantly, these supersonic

[9] United States Patent, W.E. McDermott, N.R. Pchelkin, D.J. Benard, and R.R. Bousek, "Continuous Wave Chemically Pumped Atomic Iodine Laser," No. 4,267,526, 12 May 1981; Article, W.E. McDermott, N.R. Pchelkin, D.J. Benard, and R.R. Bousek, "An Electronic Transition Chemical Laser," *Applied Physics Letters*, vol. 32, No. 8, 15 April 1978, pp. 469-470; Interview with Pchelkin, 24 Aug 1999; "A History," p. 25.

[10] "A History," pp. 25-30; "Historical Perspective," pp. 5-6; Interview with Pchelkin, 24 Aug 1999; "History-AFWL," pp. 245-248; Notes, Keith Truesdell, "On Chemical Oxygen Iodine Laser draft," 12 Oct 2005.

devices showed COIL lasers could be scaled to increase their power for weapon applications. By 1987, Dr. Keith Truesdell and other AFWL scientists assembled and tested a COIL device termed ROTOCOIL that integrated a rotating disk oxygen generator (developed by TRW Corporation, now NGST) and scalable mixing nozzle arrays (developed by Rocketdyne, now Boeing). ROTOCOIL achieved its goal of 25 kilowatts of power and was optimized at 40 kilowatts of power. The first large-scale COIL unstable resonator experiments on ROTOCOIL achieved a laser beam of near pristine quality. These advances earned the notice of Secretary of the Air Force, Edward C. Aldridge, Jr., who lauded COIL's developments.[11]

As early as 1990-91, when the Airborne Laser program began to emerge from its ALL origins, the Air Force immediately considered COIL as the leading candidate for the ABL's weapon system. By the early 1990s, COIL's technology had matured to a reliable, stable, and safe device, which also offered substantial weight savings and a relatively minor cost of operation in comparison with other chemical laser devices. Its scalability to weapon system power levels made it the system of choice. When compared to the original ALL CO_2 laser, COIL was considerably less bulky, lighter, and its continuous short wavelength provided better beam propagation through the atmosphere and could generate considerably more power, meaning longer effective ranges.[12]

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[11] "History-AFWL," pp. 246-251; History, AFWL/HO, "History of the Air Force Weapons Laboratory, 1 October 1986—30 September 1988," vol. I, 1989, pp. 203-209; History, AFWL/HO, "Terminal History of the Air Force Weapons Laboratory, 1 October 1988—13 December 1990," vol. I, 1991, pp. 234-236; Truesdell, notes/comments, 12 Oct 2005; Paper, K.A. Truesdell, C.A. Helms, and G.D. Hager, "Coil Development in the U.S.A.," presented at the 25th AIAA Plasmadynamics and Lasers Conference, 20-23 June 1994, pp. 5-9.

[12] History, PL/HO, "History of Phillips Laboratory, 1 October 1989—30 September 1991," vol. I, 1992, pp. 323-324; History, PL/HO, "History of Phillips Laboratory, 1 October 1992—30 September 1993," vol. I, 1994, pp. 95-96; "Directed Energy," p. 233.

During the 1990s, significant improvements occurred with COIL. In 1993, power operations were sustained for over two minutes, and the following year, Drs. Charlie Helms and Keith Truesdell of AFWL's descendent Phillips Laboratory developed VertiCOIL, which continuously lased for almost an hour, while its closed-loop system permitted chemicals to be extracted and reused. Because COIL operated in relatively low temperatures, plastic parts replaced metal ones to increase weight savings and to decrease costs. In 1995, Drs. Keith Truesdell, Gordon Hager, and Charlie Helms of the Phillips Laboratory built the RADICL or research assessment device improvement chemical laser, a 20-kilowatt supersonic COIL used to develop new laser nozzles and demonstrate other efficiency improvements. The RADICL's laser was transmitted via fiber optics, and used to demonstrate significant commercial applications, including cutting thick metals under hazardous conditions, such as dismantling contaminated nuclear power plants. RADICL was also used to investigate nitrogen diluents, instead of the scarcer and more expensive helium, which eventually led to the Airborne Tactical Laser technology.[13]

Air Force Research Laboratory Directed Energy Directorate scientists under the leadership of Dr. Steve Lamberson and then Dr. Keith Truesdell continued to advance the laser to its development as a weapon system. These advances resulted in awarding the Airborne Laser contract, which tasked Northrop Grumman to develop a megawatt-class COIL weapon. Northrop Grumman, which had already demonstrated the COIL Baseline Demonstration Laser module, proceeded to develop the Flight-weighted Laser Module or FLM, which was based on the Transverse Flow Uniform Droplet Oxygen Generator developed by Dr. William Thayer of STI Optronics under contracts from the

[13] History, PL/HO, "History of Phillips Laboratory, 1 October 1993—30 September 1994," vol. I, 1995, pp. 119-121; History, PL/HO, "History of Phillips Laboratory, 1 October 1995—30 September 1996," vol. I, 1997, pp. 389-393; Truesdell, notes/comments, 12 Oct 2005; Article, John Del Barga, Gordon Hager, Kip Kendrick, "Advances in Chemical Oxygen-Iodine Laser Technology," *Air Force Research Laboratory Technology Horizons*, Dec 2001, pp. 22-23.

Phillips Laboratory. The FLM served as the basic building block for the laser weapon, with several modules linked to achieve the necessary power levels. In September 1997, Team ABL proved the critical singlet oxygen generator achieved its necessary production levels, and the FLM reached "first light" or its successful first operation in June 1998. That September, the FLM produced 110 percent of its design power, and by March 2002, reached 118 percent. The ABL's COIL weapon system, which transitioned from an Air Force systems program office to DoD's Missile Defense Agency, was well on its way.[14]

In sum, COIL showed what an Air Force laboratory could do best. Creative Air Force minds had invented the first COIL laser at AFWL. As an in-house program, COIL provided practical experience for over two decades to Air Force scientists and technicians, both blue-suiters and civilians. The Air Force laboratory system, with additional funding from the Air Force Office of Scientific Research, had steadily nurtured and developed the technology. Air Force researchers innovatively improved the device to make it more efficient, powerful, and less expensive. Although initially COIL had started as a candidate for a ground-based laser system, it evolved as the prime laser for airborne applications, and potentially even for use in space. On top of these noteworthy events, COIL was also ready to transfer to the civilian commercial market, with the potential to revolutionize industrial use of lasers. Undeniably, over the course of 25 plus years, COIL set an impressive standard for military research and development efforts.

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[14] History, AFRL/HO, "History of the Air Force Research Laboratory, October 1997—September 1998," vol. I, Apr 2000, p. 108. "Directed Energy," pp. 233-234; Truesdell, notes/comments, 12 Oct 2005.

Composite Aerospace Structures

Composite materials, or fibers suspended in matrix resins, have been the subject of Air Force research for decades. The results were the product of a long-standing and close collaboration between the predecessors of today's Air Force Research Laboratory Materials (AFRL/ML) and Air Vehicles (AFRL/VA) directorates. The former led the development of new composites, while the latter was charged with their application to aircraft (and later, spacecraft) structures. The search for appropriate materials was a concern of all aircraft designers, even well before the Wright Brothers. Then, structural strength and light weight were paramount, as the power plants of the day did not provide enough thrust to lift heavy structures. Unsurprisingly, lightweight woods, with which there existed extensive expertise, were the material of choice. Some early experimenters in Europe tested some metal-skinned designs prior to and during World War I, but met with only limited success. It took the United States a decade after war's end to seriously design metal aircraft. After that point, the aluminum, stressed-skin aircraft came to dominate the skies, with a few notable wooden exceptions like the Lockheed Vega and DeHavilland Mosquito.[1]

Though some structural engineers consider wood a composite, the first true non-metallic, composite aircraft was the German-designed Horten Ho V, which had a short-lived and unremarkable existence. Since the early 1930s, the Horten brothers experimented with flying wing aircraft, with an eye toward eventually selling one to the Luftwaffe as a fighter. Their V model was first designed and built using fabric-covered D-tubes molded from paper-filled phenol resins. The selection of this material was perhaps done as a weight-saving measure, as the

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[1] Book, James J. St. Peter, *The Flight Dynamics Laboratory: Evolution of an Engineering Miracle* [hereafter cited as *Engineering Miracle*], (WPAFB, OH: Flight Dynamics Laboratory), Oct 88, p. 181; Paper, Nicholas J. Hoff, "Innovation in Aircraft Structures – Fifty Years Ago and Today" [hereafter cited as "Aircraft Structures"], AIAA 84-0840, 1984, pp. 1-5.

prototype was a glider and the Horten brothers' workshop had little experience in metal working. For that reason and a lack of strategic metals, later models devised during World War II were made of wood. The Horten aircraft were better known as some of the earliest flying wings, rather than for their contributions to composites technology.[2]

The Second World War was a catalyst for technological development in many fields, including composite materials. In 1941, Army Air Force General Henry H. "Hap" Arnold approached his laboratories at Wright Field to investigate suitable substitutes for strategic war materials. The Materials Laboratory was then the focal point for such research and had in fact been interested in glass fibers for reinforced plastics since the later 1930s (when it was known as the Materials Branch). Arnold initiated a task force at Wright Field specifically to examine the use of plastics and reinforced composites for aircraft applications. The Aircraft Laboratory (an AFRL/VA predecessor) coordinated on this task force to create more efficient structures, better electrical insulation, and electromagnetically transparent materials. The labs intimately involved industry with this project, for it was industry that had expertise in the use and manufacture of these materials. The first application for composites, using a special type of Owens-Corning-produced fiberglass-reinforced polyester, was for aircraft radomes. By late 1942, various aircraft companies were using reinforced plastic components in their military aircraft. The following year, the Wright Field labs initiated in-house projects for the fabrication of reinforced plastic primary structures. The first product was an aft fuselage for the Vultee BT-15 trainer aircraft, made of glass-fiber-reinforced plastic. Built in the labs and tested in the Aircraft Laboratory, this material had a strength-to-weight ratio 50 percent better

[2]   Brfg, Donald Paul, AFRL/VA, and David M. Pratt, AFRL/VAS, "The Evolution of Structural Design Concepts History 1903-1990" [hereafter cited as "Evolution"], n.d.; Website, Smithsonian National Air and Space Museum, "Horten Ho 229 V3," n.d., available on the internet: http://www.nasm.si.edu/research/aero/aircraft/horton_229.htm, as of 29 Nov 05.

than the original aluminum skin. The Aircraft Lab flight tested the modified BT-15 in March 1944, making it the "first major fiber reinforced plastic structural component of an aircraft to be developed and flight tested." The material also proved its value as wing structures on an AT-6 Texan trainer, fabricated and flown by the labs in 1945. That work opened the door for composite structures and, by 1948, for supersonic applications and solid rocket motor cases.[3]

Despite this early work, composite materials did not come into widespread use until after the early 1960s. The labs at Wright-Patterson continued to conduct research and other countries, particularly Germany and Japan, made good use of fiberglass for glider aircraft since the 1950s. It was the issuance of the seminal "Project Forecast" in 1963 that began in earnest a concerted effort to develop composite aircraft structures. That study identified key emerging technologies that would affect the Air Force over the next decade. Advanced composite materials were on that list, thanks to the lab's advocacy. The fallout from Project Forecast included the establishment of advanced composites research organizations in both the Materials Laboratory and the Flight Dynamics Laboratory (a successor to the Aircraft Lab), and formalized interchange between those labs "to ensure the orderly development of structural composites and the transfer of knowledge." By the end of the 1960s, composites had come close enough to the forefront of aerospace research for one prominent British lecturer to declare," Although we shall still have metal aircraft for many years to come, quite new materials are beginning to appear and they have as many advantages over metal as metal had over wood." Though his statement may appear obvious given the ubiquity of composites in aircraft today, at the time aluminum, titanium,

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[3] *Engineering Miracle*, pp. 182, 186; Manuscript, Dr. James F. Aldridge, ASC/HO, "USAF Research and Development" [hereafter cited as "R&D"], 1997, pp. 17-19; Paper, n.a. [AFRL/ML], "A Condensed History of the Air Force Materials Laboratory/Directorate" [hereafter cited as "Condensed History"], n.d., pp. 6-9.

and other advanced metal alloys were dominant in production and research, making this "obituary" for metal aircraft remarkably visionary.[4]

One of the first of the advanced composite materials developed through Materials Lab efforts and taken advantage of by the Flight Dynamics Lab (FDL) for structural use was boron fiber in epoxy. Lab effort cut the price of this material by three-fourths from 1965-1968, instigating the development and testing of boron-epoxy on an experimental horizontal stabilizer for the F-111 fighter bomber in 1967. This was followed by F-111 flight testing of a boron-epoxy airflow deflector door, landing gear door, and wing trailing edge panel. The results were encouraging enough to begin in-service evaluations of the composite – one of the first such programs for composite structures. The FDL devised a boron-epoxy rudder for the F-4, 36 percent lighter than the production counterpart, and subjected it to rigorous in-house testing before deploying prototypes to the field for a 6-year evaluation. The program ran from 1968-1974 and provided valuable data on the long-term issues associated with composites. McDonnell-Douglas subsequently used boron-epoxy in the F-14 and F-15 fighters for their horizontal stabilizers in the early 1970s. That material was also demonstrated or put into service for various components of the F-111, B-1, and A-7. The FDL remained involved with these aircraft well after their composite components went into service. Some long-term issues laid bare only through long service lives became the subjects of evaluation and redesign programs within the labs, which were able to subsequently identify and address the problems. Today, the Air Vehicles Directorate performs the same function for the older legacy aircraft and newer ones like the B-2. As composite structures like boron epoxy came into more frequent use by the early 1980s, the Flight Dynamics Lab created a program for the assessment of battle damage repair

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[4] "Aircraft Structures," pp. 6-9; "Condensed History," pp. 10-13; "R&D," pp. 19-20; *Engineering Miracle*, pp. 186-187; Article, Marcus Langley, "The History of Metal Aircraft Construction," *Aeronautical Journal of the Royal Aircraft Society*, vol. 75, Jan 1971, p. 28; "Evolution."

techniques for composite structures at the behest of the Air Force major commands. The lab's engineers subjected various components to ballistic damage and evaluated the effectiveness of repair techniques. The lab program validated repair procedures developed at the labs and elsewhere for the A-7 and F-15 boron-epoxy parts, among others.[5]

Boron-epoxy structures were eclipsed by carbon (graphite) epoxies in the 1970s as the most cost-effective advanced composite material. The FDL was engaged in many programs during that decade to demonstrate the utility of carbon composites. One of the first to be a significant technical breakthrough was the development and in-house testing of a graphite-epoxy main landing gear. The results showed a minimum 25 percent weight savings, with other components doubling the fatigue life. Like they did with boron-epoxies, aircraft contractors employed the new graphite-epoxy on the latest generation of aircraft, such as the B-1, F-16, and F-15. In the case of the latter, the Flight Dynamics Lab designed, developed, and tested a composite speedbrake to replace the baseline aluminum version that failed during tests. The lab's product was later incorporated into the production F-15s. FDL demonstration programs of composite wing and forward fuselage structures for advanced fighters proved the viability of these full-scale components and their low-cost, low-weight characteristics in larger applications. That effort led to the Navy's acceptance of F-18 and AV-8B Harrier designs with carbon epoxy primary wing box structures.[6]

By the mid-1980s, programs like those in the Air Force labs and the limited operational use of carbon composites fairly well proved the performance benefits

[5]   "R&D," pp. 29-32, 59, 64-65; "Condensed History," pp. 11-12; *Engineering Miracle*, pp. 188-191; "Evolution;" History, AFSC/HO, "History of the Aeronautical Systems Division October 1982-December 1983 (Fiscal and Calendar Year 1983) Part II: The Air Force Wright Aeronautical Laboratories," Oct 82- Dec 83, pp. 30-31.

[6]   "R&D," pp. 59-65; "Evolution."

of composite materials. Emphasis from that point shifted to lowering development and production costs and finding even more applications for composites. Some of these advanced applications included: the MX missile deployment module, the Global Positioning System (GPS) satellite structure, the NAVSTAR satellites, the B-2 stealth bomber, and the forward-swept wings of the X-29 technology demonstrator -- the design for which was not feasible without such materials. The FDL studied and developed new concepts, such as metal matrix composites (MMCs), carbon-carbon composites (CCCs), titanium-matrix composites (TMCs), ceramic matrix composites (CMCs), and thermoplastics and similar materials for use in advanced aircraft transparencies. Recent major efforts like the Composites Affordability Initiative addressed manufacturing costs in a systematic manner, while others, such as Z-fiber research, sought to improve the deficiencies of composites.[7]

The success of the Air Force laboratories' research in composites is evidenced by the depth of penetration of those materials into the modern generation of aircraft. In the F-22, for example, composites make up one-quarter of the weight of its structure. That number jumps to 37 percent for the B-2 and over 40 percent for the V-22 Osprey. Even these figures probably undervalue the portion of composites in aircraft since these materials are used precisely because they weigh less than aluminum or titanium. It was the cooperative effort of today's Materials Directorate, Air Vehicles Directorate, and their industrial partners that developed, tested, proved, and implemented the composites that are now an integral and invaluable part of aircraft design.[8]

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[7]   "R&D," pp. 63-69; "Evolution."

[8]   "Evolution."

Computational Fluid Dynamics for Design and Analysis

Since the Wright Brothers, the wind tunnel has been the most critical tool for aircraft design and analysis, but about fifty years later, computational fluid dynamics (CFD) began to emerge as the latest revolutionary diagnostic tool for aircraft. Computational fluid dynamics is defined as the science of determining a numerical solution to the governing equations of fluid flow (called the Navier-Stokes equations) while advancing the solution through space or time to obtain a numerical description of the complete flow field of interest. Aerodynamicists, including those of the Air Force, were among the first to embrace early computers, which could solve tedious, but necessary, equations associated with understanding the motion of fluids about an aircraft. Though CFD came to be synonymous with massive computing power, it was not always the case. The antecedents for CFD harked back to the 1910s, decades before the first electronic computer, with the first suggested "approximate arithmetical solution by finite differences of physical problems involving differential equations," specifically in that case for stresses in a dam. A series of other scientists around the world further advanced the understanding of the fundamental issues.[1]

The advent of the first electronic computers in the 1940s made the solution of partial differential equations through finite-difference methods practical. The famous ENIAC was the first such computer to make calculations for fluid dynamics. One CFD pioneer remarked, "The advent of the computer has revolutionized a wide range of scientific research; however, fluid dynamics is the most affected by this revolution." From the point of ENIAC on, the concepts and theories underlying CFD advanced along with the tools for deriving solutions. A scientist at Los Alamos National Laboratory, F. H. Harlow, was the first to propose breaking down fluid dynamics into discrete mass particles moving

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[1]   Article, Joseph S. Shang, "Three decades of accomplishments in computational fluid dynamics" [hereafter cited as "Three decades"], *Progress in Aerospace Sciences*, vol. 40, 2004, pp. 174, 194.

through fixed cells, called the Particle-in-Cell (PIC) method. That technique became the basis for "the future development of all CFD algorithms and numerical procedures." The 1960s saw a wave of improvements in CFD methodology, especially for less understood phenomena, such as the point of flow separation, boundary layer/shock wave interaction, and supersonic flow. Techniques for calculating three-dimensional flows were also developed during that time period. Perhaps the leading organization for CFD development at the time was the NASA Ames Research Center, whose work spread throughout the space agency and to each of the military research laboratories, who to that point had accomplished little significant work in the field. Interestingly, it was the government labs that pioneered CFD, which was subsequently adopted by academia and industry.[2]

The Air Force's Flight Dynamics Laboratory (FDL) at Wright-Patterson AFB delved into computational fluid dynamics as it began to develop hypersonic and lifting body aircraft in the 1960s and 1970s. That work was coincident with groundbreaking developments in CFD algorithm research at NASA Ames, particularly by Robert McCormack. The leading FDL scientist in CFD, Dr. Joseph Shang, described this period as one of "peer review and open debate," which his lab was quick to take advantage of in resolving issues with their increasingly complex aerospace vehicle design. Of the various CFD methods in development, the FDL focused on three that became the most widely used. The Euler Approximation was a sophisticated calculation used for streamlined bodies. The most complex method was the Navier-Stokes method, considered "the limit of the macroscopic representation of gas dynamics." The Parabolized Navier-Stokes method was a simplification that excluded time-dependent phenomenon and certain complex flows. Its advantage was that it cost one-fifth as much as the full Navier-Stokes equations. It was most frequently used in analyzing supersonic and hypersonic vehicles. All three methods were used in the lab for

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[2]   "Three decades," pp. 174-176.

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both data acquisition paralleling wind tunnels and for "the more important function of configurational synthesis based upon the definition of idealized characteristics for future configurations." The FDL's participation in the wider CFD community facilitated the transfer of lab-developed techniques to outside organizations and advanced the lab's own knowledge of other developments.[3]

Though the theories, algorithms, and computational power improved through the 1970s, the state-of-the-art still limited the applications to either simplified bodies or more complex components, but not entire, real-world bodies. It was on these limited applications that the FDL and rest of the field cut their teeth. Then, as now, CFD researchers considered the understanding of turbulence the "Achilles heel of CFD as a scientific discipline," as it was for physics in general. The FDL therefore directed its efforts at using CFD to better predict turbulence and flow separation. One outstanding such project involved the simulation of a three-dimensional hypersonic compression corner, which was a previously unsolvable problem. This was the first numerical solution of the three-dimensional compressible Navier-Stokes equations. Its researchers also used this type of numerical solution for turbulent ramp and shock-induced separated flows. That achievement "was a milestone in the ability to compute the entire flow field over a complete aircraft configuration." Another step in realizing that ultimate goal was the complementary development of analytical methods for solving problems, such as axisymmetric nozzle boattail flow field. The FDL verified their computational results with wind tunnel data, a comparison that was used consistently in the first few decades of CFD to verify the computer models.[4]

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[3]   "Three decades," pp. 177-180; Manuscript, Dr. James F. Aldridge, ASC/HO, "USAF Research and Development" [hereafter cited as "R&D"], 1997, pp. 79-80.

[4]   "R&D," p. 80; "Three decades," pp. 177-178, 185.

While the CFD community solved the initial critical aerodynamic concepts for vehicle components during the 1970s, it was during the succeeding decade that the full potential of computational fluid dynamics for design and analysis was first realized. At the Flight Dynamics Lab, a series of major programs achieved remarkable advances, helped in large part through the acquisition of the revolutionary computing power afforded by the first generation Cray "supercomputer." One of the first milestones achieved using the Cray was the solution of spike-tipped body "buzz," relevant to both spike-tipped configurations and to re-entry nose cones. Like turbulent flow, aerodynamic buzz was a long-standing mystery. The FDL analyzed this problem through the numerical solution of the time-dependent Navier-Stokes equations. The result was the first buzz prediction method that accurately simulated true flight conditions. It also led to the improvement of viscous flow field solutions and computer programs. A number of other applications at the FDL demonstrated the utility and versatility of CFD. These included flow and heat transfer analysis of maneuvering reentry vehicles for the Ballistic Missile Office (BMO). It was this program that led to the lab's development of the parabolized Navier-Stokes code that was adopted as a standard for the field and was used both for the BMO and the National Aerospace Plane (NASP). FDL researchers additionally applied their numeric methods to axisymmetric nozzles in a supersonic external stream – the first time the full Navier-Stokes solutions were completed for this problem. It demonstrated that numerical solutions were highly applicable in investigating nozzle performance and aft-end drag problems.[5]

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[5] "R&D," pp. 81-83; "Three decades," p. 182; Book, James J. St. Peter, *The Flight Dynamics Laboratory: Evolution of an Engineering Miracle* [hereafter cited as *Engineering Miracle*], (WPAFB, OH: Flight Dynamics Laboratory), Oct 88, pp. 142-143; History, AFSC/HO, "Fiscal Year 1982 History of the Air Force Wright Aeronautical Laboratories, 1 Oct 81- 30 Sep 82," vol. I, pp. 90-91; History, Dr. James F. Aldridge, ASC/HO, "History of the Aeronautical Systems Division, January – December 1986, Part II: The Air Force Wright Aeronautical Laboratories, January 1984 – December 1986," Jul 1987, vol. 1, p. 167.

The most significant breakthroughs made by the Flight Dynamics Lab in CFD during the 1980s were the solutions of complete vehicles. In 1984, lab scientists began a concerted effort to duplicate wind tunnel results of an air vehicle using CFD numeric simulation. They chose to model the X-24C lifting reentry vehicle designed and flown by the lab in the 1970s. It made an excellent basis for comparison because of the reams of wind tunnel data obtained for it during its testing. The lab used the solution of the full Navier-Stokes equations to compute the aerodynamics of a complete, three-dimensional vehicle for the first time ever. The work resulted in complete data for all aspects of airflow about the vehicle, including shock waves and interference heating. Those data corresponded closely with the original wind tunnel analyses. Moreover, the detailed results permitted visual representation of that data on computer displays. The X-24C work was considered a truly historic event in CFD: the first such complete configuration calculated by the CFD solution of the Navier-Stokes equations. It was a major step in demonstrating that computational fluid dynamics were an accurate and cost-effective alternative to wind tunnels. It also offered a means for analyzing designs without resorting to the traditional, lengthy trial-and-error method. The FDL's Aeromechanics Division took that program a step further in 1986 in analyzing an F-16 fighter, an even more complex aircraft than the X-24C. The division used a computer code developed in-house by Dr. Shang, which was an efficient program for computing three-dimensional flow. This, too, was an historic achievement, as it was "the first time a complete flow field configuration flow field had been calculated for a fighter-type configuration." The project took two years to complete, including 11 months of computing time just to generate the flow field grid, 3 months for processing the actual simulation, and another 3 months for validating and interpreting the results. The data again closely matched that seen in the wind tunnel. The lab worked to reduce the time required for computation by taking a new approach to grid computation. It developed unstructured grid technology that simplified the gridding process,

reducing the time to a small fraction of older methods. The lab's new grid-generation techniques made widespread transition to other organizations.[6]

The multi-disciplinary nature of computational fluid dynamics made its tools and techniques well suited to broader applications. The Flight Dynamics Lab and its successor, the Air Force Research Laboratory Air Vehicles Directorate (AFRL/VA), were at the forefront of broadening the field to include other computational sciences. Aeroelasticity was one natural extension for the lab, as it had long dealt with the complicated phenomena of buffeting and flutter, two key aspects of aeroelasticity. Solving those problems required the simultaneous solution of both structural dynamics equations with the Navier-Stokes or Euler equations. The NASP program of the late 1980s pushed the understanding of hypersonic flight, leading researchers to use CFD-like codes for aerothermodynamics. This field added the equations of chemical kinetics into the solution. The final aspect of obtaining a full understanding of flow about a vehicle involved the establishment of computational magneto-fluid dynamics, or CMD. CFD researchers had only recently delved into this modeling of plasma as it related to hypersonic flight. Finally, CFD techniques made significant inroads in the area of computational electromagnetics (CEM). The CFD methods were directly applicable to the solution of the Maxwell equations that govern electromagnetics and were able to successfully model the radar cross-section of complex forms. In 1992, future AFRL commander Richard Paul suggested to Joseph Shang that he try his hand at CEM to improve stealth research. By the end of the year, Dr. Shang had solved the (general) time-dependent Maxwell equations. By 1998, Shang and his lab team at AFRL/VA had progressed to very complex forms. That year, they completed one of "the most complex and difficult

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[6] "R&D," pp. 81, 85-86; *Engineering Miracle*, pp. 142-143, 233-234; "Three decades," p. 182; Article, John D. Anderson, Jr., "Computational Fluid Dynamics," in Book, *Technology and the Air Force: A Retrospective Assessment*, ed. by Jacob Neufeld, et al. (Washington, DC: Air Force History and Museums Program), 1997, pp. 293, 296.

electromagnetic scattering simulations ever attempted," in using the B-1B bomber as their subject. The results matched closely with those obtained from a radar range, thus validating the VA algorithms.[7]

Dr. Joseph Shang summed up the progress made in computational fluid dynamics since its practical creation in the 1960s, "A dream that one can evaluate the aerodynamic performance of any complete aircraft in two weeks has been realized over the past 30 years." This was a remarkable achievement made by a widespread community composed of military, civilian, academic, and corporate laboratories. By the late 1990s, it was possible to consider CFD a true alternative to traditional wind tunnel testing, if not as a complete replacement. The two techniques have emerged as complementary means of efficiently and accurately designing new aircraft, or more fully understanding the performance of existing ones, such that both have become indispensable tools in aerospace engineering. The Air Vehicles Directorate and its predecessors were at the leading edge of progress in both the application and development of CFD for aircraft design and analysis and has continued to push the field in applications in all the computational sciences.[8]

[7]   "Three decades," pp. 187-193; Paper, Joseph S. Shang, "Shared Knowledge in Computational Fluid Dynamics, Electromagnetics, and Magneto-Aerodynamics," AIAA-2001-2522, Jun 01, pp. 1-3, 9; History, AFRL/HO, "History of the Air Force Research Laboratory, 1 October 1997-30 September 1998," Vol. I, Apr 00, pp. 364-368.

[8]   "Three decades," pp. 184, 193-194.

Computer Mouse and a New Paradigm

No one story related to AFOSR basic research funding so typifies and exemplifies the significant role of the individual program manager than the funding of the man who invented the computer mouse and, more significantly, wrote the AFOSR-sponsored blueprint of how man can better interface with the computer. In short, with the support of the Air Force Office of Scientific Research, Dr. Douglas Engelbart changed the paradigm of the relationship between man and computer.

In 1960 AFOSR program manager, Mrs. Rowena Swanson, and her supervisor, Dr. Harold Wooster, Director of AFOSR's Information Sciences office, decided to fund Doug Engelbart's vision of "augmenting the human intellect."[1] It was only five years previous to this that Engelbart had received his doctoral degree in electrical engineering from the University of California, Berkeley. According to Engelbart, he reluctantly settled for an "EE" degree, simply because there was no such thing as a computer-related Ph.D. He then went on to work at the Stanford Research Institute (SRI), at Menlo Park, California.[2] It was in the late summer of 1959, while at SRI, that Engelbart was given a paper titled "Shrinking the Giant Brains for the Space Age," by Jack J. Staller.[3] Staller discussed—at this very early stage—the compression of a "room full of digital computation equipment" into ever smaller sizes, "or perhaps complete computers

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[1]   Interview, Dr. Douglas Engelbart with Dr. Bob White, 1 Nov 2005; Newspaper article, Y. S. Lamb, *Washington Post*, "Harold Wooster, 86; Computer Pioneer," 3 June 2005, p. (Metro) 37; Web article, Douglas C. Engelbart, McDonnell Douglas Corporation, "The Augmented Knowledge Workshop" [hereafter cited as "Augmented Knowledge"], 1986, at www.diku/dk/undervisning/2003f/datV-system/p73-engelbart.pdf as of 25 Oct 2005.

[2]   Interview, Engelbart with White; "Augmented Knowledge."

[3]   Web article, Jack J. Staller, American Bosch Arma Corporation, "Shrinking the Giant Brains for the Space Age," 30 June 1959, at http://sloan.stanford.edu/mousesite/EngelbartPapers/B10_F3_GiantBrain.html as of 25 Oct 2005.

in fractions of cubic inches."[4]   But this idea was not new to Engelbart, for he came to much the same conclusion on February of the same year, "...that a relentless and inevitable increase in computing capacity would result from the continuous shrinking of the transistor [and that] with this increase in capacity, computers would soon be powerful enough to augment the human intellect."[5] As later commentators in the computer industry would observe, what Engelbart had prophesized in 1959, was nothing less than what Gordon Moore had published a full five years later in *Electronics* magazine, which came to be known as "Moore's Law."[6]

Thus it was that AFOSR, with its relatively new Information Sciences directorate, issued a research contract (Number AF49 (638-1024)) to Engelbart in the spring of 1960. The initial connection between AFOSR and Engelbart is lost to history, and Dr. Engelbart readily admits that he cannot remember how the relationship first began.[7]   Engelbart, though, clearly remembers the "many proposals" he submitted in 1959 to various funding agencies, including AFOSR, in which he outlined the development of a conceptual framework for the use of "computers for intellectual collaboration."[8]   Only one agency he applied to responded positively—and that was AFOSR. In the words of Engelbart himself,

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[4]   *Ibid.*

[5]   Web article, Bill Joy, Kleiner, Perkins, Caufield and Byers, Inc., "The Dream of a Lifetime," *TechnologyReview.com,* Aug 2005, at www.technologyreview.com/articles/05/08/issue/review_dream.0.asp as of 25 Oct 05.

[6]   *Ibid.*

[7]   Monograph, Stan Augarten, "Douglas Engelbart and the Invention of Collaborative Computing," *Group Computing Magazine,* July/August 1996, p. 4.   An Air Staff (Pentagon) computer research contract was issued to Engelbart in February 1959. See: Database document, n.a. [Defense Technical Information Center], "Douglas Engelbart: High Speed Components for Digital Computers," Feb 1959.

[8]   Interview, Engelbart with White; Monograph, Stan Augarten, "Douglas Engelbart and the Invention of Collaborative Computing," *Group Computing Magazine,* July/Aug 1996, p. 3.

had AFOSR had not been there to fund his work, there would have been no seminal "Augmenting Human Intellect" paper as it took "many, many months to work it all out...there is no way it would have been possible had not AFOSR given me the space and time to do it."[9] It also is quite possible that the mouse would not have come about when it did, and that there may have been a wholly different paradigm approach relative to the man and machine interface.[10] Engelbart noted that once AFOSR funding began, which "carried me for several years," he worked quite closely with AFOSR's Dr. Wooster and Mrs. Swanson.[11]

A very interesting and humorous anecdote told by Dr. Engelbart concerned a story relayed to him by AFOSR program manager Rowena Swanson. It seemed that AFOSR Information Sciences Director, Harold Wooster was not overly fond of the prospect of funding Dr. Engelbart's idea, and during the initial evaluations Wooster would place the Engelbart proposal in the "rejection" pile, whereupon Mrs. Swanson would surreptitiously place it back in the "accepted for final review" pile. It seems that Mrs. Swanson knew a good thing when she saw it, and Dr. Wooster was soon convinced of the merits as well.[12]

What Mrs. Swanson, and ultimately, Dr. Wooster, grew to appreciate, was Engelbart's belief in the potential of computers to assist people in complex decision-making. Using AFOSR funds initially, and eventually with some SRI support, Dr. Engelbart performed his research full-time and forwarded his study, "Augmenting Human Intellect: A Conceptual Framework," to AFOSR. This

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[9]   Interview, Engelbart with White.

[10]   *Ibid.*

[11]   Interview, Engelbart with White; "Augmented Knowledge."

[12]   Interview, Engelbart with White.

report, published in 1962, served as a seminal roadmap for developing computer technologies.[13]

Dr. Engelbart believed that the complexity of problems facing mankind was growing faster than the ability to solve them. He envisioned that future problem solvers would use computer-aided work stations to augment their decision-making—in fact he jokingly referred to his computer as "augment."[14] But to facilitate and aid future problem solvers, an easier way to interact with the computer was a necessity. Engelbart saw that computer users would need the ability to interact with computer information displays using some sort of device to move a cursor on the screen, which would be "...held like a pencil and, instead of a point, have a special sensing mechanism that you can pass over a line of the special printing from your writing machine (or one like it). The signals which this reading stylus sends through the flexible connecting wire to the writing machine are used to determine which characters are being sensed, and thus cause the automatic typing of a duplicate string of characters." We know that device today as a mouse.[15]

The first computer mouse prototype was developed in 1965 as a direct follow-on experiment to find better ways to "point and click" on a computer display screen. Made out of wood, the single button mouse was but a small part of Engelbart's long range vision to improve human interaction with computers, but it was a revolution in and of itself.[16] He developed the mouse "as part of an

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[13]   *Ibid.*; Summary report, D. C. Engelbart, Stanford Research Institute, "Augmenting Human Intellect: A Conceptual Framework" [hereafter cited as "Conceptual Framework"], Oct 1962.

[14]   Interview, Engelbart with White.

[15]   Interview, Engelbart with White; "Conceptual Framework," p. 13.

[16]   Brfg, Dr. J. Janni, AFOSR/CC, "Air Force Basic Research: Selected Success Stories," 1999, slide # 5.

explicit search for optimum screen selection techniques in association with an online application framework.[17] Engelbart's seminal paper also foresaw what he described as "several people working together from working stations that can provide inter-communications via their computer or computers.[18] Engelbart's 1962 description of individuals, or various teams of individuals, simultaneously working on the same project, was far ahead of its time: "The whole team can join forces at a moment's notice to pull together on some stubborn little problem, or to make a group decision."[19] While Engelbart may have called it "intercommunication via computer," we know it better today as computer networking.

It took quite a while for Douglas Engelbart to achieve the recognition that he deserved. For his lifetime accomplishments, Engelbart won the 2002 Turing Award, which is the Nobel Prize equivalent for computer scientists. He was also inducted into the National Inventors Hall of Fame, and in 1997, he won the Lemelson-MIT $500,000 prize.[20]

Dr. Engelbart's AFOSR-funded 1962 report contains what many, at the time, would have considered very fanciful projections, and impossible predictions. Years later, Engelbart noted that the furtherance and implementation of the ideas in his 1962 report could not have been appreciated, nor made possible, without AFOSR program managers, whose "....intuition and judgment in what they would

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[17] "Augmented Knowledge."

[18] "Conceptual Framework," p. 105.

[19] *Ibid.*

[20] Web article Christina Engelbart and Douglas Engelbart, Bootstrap Institute, "A Lifetime of Pursuit," 24 June 2003, at: www.bootstrap.org/chronicle/chronicle as of 25 Oct 05.

support..." were crucial.[21] Engelbart found such people and an organization in AFOSR.

[21] Interview, Douglas Engelbart, SRI, with Henry Lowood and Judy Adams, Stanford Oral History Project, Stanford University, 14 Jan 1987.

Dip-Pen Nanolithography: Manipulating Molecules and More

Dip-Pen Nanolithography (DPN) is a technology that builds nanoscale structures and patterns by drawing molecules directly onto a substrate. The process is a notable advance in nanofabrication technology that has significant potential to bring nanofabrication from the research laboratory to an industrial setting. This is because the process combines high resolution, accuracy, scalability to high throughput (with parallel pen systems), material flexibility, and ease of use.[1] Basically, it's the world's smallest pen, and DPN is the breakthrough in the nanotechnology world that may facilitate the creation and development of smaller, lighter, faster and more reliable Air Force weapons systems, as well as a myriad of commercial applications.[2] The following relates the fortuitous research path that brought about the discovery and refinement of Dip-Pen Nanolithography technology due directly to AFOSR funding, and the inherent flexibility of AFOSR program managers to shift the focus of a research program when conditions warrant.

Over the past five years, one of AFOSR's most revolutionary and intriguing programs evolved from a grant from the Chemistry and Life Sciences Directorate (AFOSR/NL).[3] Dr. Chad Mirkin, (Northwestern University's Director of the Institute for Nanotechnology) and his team, have performed groundbreaking research in nanotechnology that could result in major Air Force impacts across a wide spectrum of applications: weapon and space systems, electronic circuit

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[1] Website, NanoInk, Inc., "NanoInk Backgrounder," 1 Oct 2005, at http://www.nanoink.net/2310_backgrounder.html as of 4 Oct 05.

[2] Web article, Dr. Hugh DeLong, AFOSR/NL, "Dip-Pen Nanolithography - Air Force to Benefit with Smaller, Lighter, Less Costly Systems" [hereafter cited as "Nanolithography"], *AFRL Technology Horizons*, Mar 2000, at http://wwwafrlhorizons.com/Briefs/0001/OSR9902.html as of 4 Oct 05.

[3] Grant case file, Dr. Hugh DeLong, AFOSR/NL, No. F49620-99-1-0071, "Mirkin: Northwestern University," 15 Oct 1998.

miniaturization, high density storage devices, nano-scale power sources and assemblies, unbreakable cryptography, wide-ranging, failsafe and inexpensive bio-warfare sensory devices, and advanced medical diagnosis capabilities on and off the battlefield. Essentially, Dip-Pen Nanolithography has successfully breached the limiting factor of size relating to the components that make up a device.

The roots of this program go back to late 1997 when AFOSR/NL Program Manager, Dr. Hugh DeLong, funded Dr. Mirkin's group to make a better battery— a project seemingly far removed from DPN.[4] But in the course of using an Atomic Force Microscope (AFM), to create a three-dimensional battery architecture, Mirkin's group noted that the tip of the AFM had the innate capability to precisely place items and draw lines at the nanoscale level. This was due, in part, to the collection of water on the tip of the AFM, which would act as a carrier of particles for deposition on a surface area.[5] This initial imaging was first noted by Mirkin's postdoctoral associate, Dr. Richard D. Piner, who is now part of the Department of Mechanical Engineering, Northwestern University. It was this basic research eureka moment that prompted the call from Dr. Mirkin to Dr. DeLong in early 1999, to shift the focus of their research to this new found capability.[6]

This new found capability was due to the small drop of water that condenses at the point of contact between the tip of the AFM and the surface it is moving across—or the "meniscus" as the DPN user community has termed it. Mirkin's group studied this further and found that this water is always moving as the tip moves across the surface—and, in fact, there was an inherent transport

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[4] Interview, Dr. Chad Mirkin, Northwestern University, and Dr. Hugh Delong, AFOSR/NL, with Dr. Bob White, AFOSR/PIC, 29 Sept 2005.

[5] *Ibid.*

[6] *Ibid.*

capability. There is either transport of water from the surface of the tip, to the substrate one is probing, or a depletion of water from the substrate, with the water moving up the tip, depending upon how hydrophobic or hydrophilic the substrate and tip are.[7]

Given that early finding, it was obvious that patterns could be made out of water at the nanoscale, which, by Dr. Mirkin's own admission, was interesting, but not very useful. Mirkin then took the process a step further in an attempt to create stable structures using a gold substrate, and alkanethiols—which was the beginning of Dip Pen Nanolithography (DPN). This particular step was taken because alkanethiols will chemically adsorb onto the gold, and form a strong gold/sulfur interaction. The key innovation was the incorporation of a chemical driving force to move the molecules from the tip to the surface, and once in place, anchor the "ink molecules" to the surface in the form of a stable structure. Initially, with that step, Mirkin's group was able to create patterns down to 15 nanometers in terms of resolution, which was later improved to about 10 nanometers.[8]

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[7] *Ibid.*

[8] *Ibid.* Interestingly, Hans-Jurgen Butt and Manfred Jaschke, at the Max-Planke Institute for Polymer Research, had attempted a similar experiment four years previously and tried to deposit an alkanethiol on mica, gold, and glass. They concluded that the process did not occur on gold or glass, and was uncontrollable on mica leading to the deposition of aggregates in unusual shapes and variable heights. It is still unclear why they concluded that alkanethiols do not deposit on gold because to this day it is one of the most well-studied molecules in the context of DPN. See article, Manfred Jaschke and Hans-Jürgen Butt, Max-Planck-Institute for Polymer Research, "Deposition of Organic Material by the Tip of a Scanning Force Microscope," *Langmuir*, 1995, vol 11, pp. 1061-1064.

These results were published in *Science* in 1999, and DPN was born.[9] The first patents on DPN were issued shortly thereafter.[10] In essence, Mirkin's group recognized that this was quite special in the sense that it had everything needed to make a simple, straightforward, and very flexible lithography that would allow one to pattern molecules on surfaces and do it in high resolution, near perfect registration, and to do it in direct-write rather than indirect mode. Note that most lithographies including photo-lithography, are indirect processes—they use a resist—made of a polymeric material that is damaged, or changed to create a pattern. In this case there is no resist. The molecules of choice are put on the tip, and they are directly transported to the surface, where they chemically react with the surface to give one an intentionally designed structure.[11]

Using the Atomic Force Microscope as basically an extremely small paint brush, Mirkin could spell out "AFOSR" on the nanoscopic scale—which he did. The next step was to demonstrate writing with two different inks on the nanometer length scale. For example: take a square and write two sides of it with one type of molecule—a hydrophobic one—and then change the AFM tip and put on a different ink, and finish that structure, and write the other two sides of the square with a different molecule. Then one could image the results and show that one had near perfect precision. One could not only make patterns, but one could control the chemical composition of those patterns. There are no other

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[9] Article, Richard D. Piner, Dept of Chemistry, Northwestern University, et al., "Dip-Pen Nanolithography," *Science*, vol. 283, Issue 5402, 29 Jan 1999, pp. 661-663. Also see "Nanolithography," and Article, Neil Steinberg, "NU Professor Crosses Line to Faster Computer Circuits," *Chicago Sun Times*, 29 Jan 1999, p. 15.

[10] Grant case file, Dr. Hugh DeLong, AFOSR/NL, "Mirkin: Northwestern University," No. F49620-99-1-0071, 15 Oct 1998.

[11] Interview, Mirkin and Delong with White.

tools that allow a researcher to do that on this scale.[12]   Further refinements ensued.

The initial DPN process began with one "pen" in contact with the surface area—then two pens were placed in parallel. This particular experiment also demonstrated that the degree of downward force on the pens was not critical as the meniscus was very forgiving, and the diffusion properties of the molecules filled in the surface voids as the pen was pulled away.   Therefore, any shortcomings of any massively parallel DPN array would be easily overcome by the mechanically forgiving nature of the process.   As such, it is possible to have thousands of pens operating in parallel in contact with the surface.[13]

The beginning of this part of the DPN quest was made possible when Dr. Mirkin joined forces with Dr. Chang Liu, an Electrical and Computer engineer at the University of Illinois at Urbana Champaign.   By putting thermal and electrostatic actuators on the pens, it would allow the specific control of individual or group pen placement, so that highly customized structures could be made. The refinement of this work was done between 2000 and 2003 and helped along with funding from DARPA as well as AFRL/AFOSR grants.   Renewal grants are

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[12]   *Ibid.* These and related efforts were funded by AFOSR grant No. F49620-99-1-0071.   Also see Article, Dana A Weinberger, Seunghun Hong, Chad A. Mirkin, and B. W. Wessels, Northwestern University, and Thomas B. Higgins, Harold Washington College, "Combinatorial Generation and Analysis of Nanometer- and Micrometer-Scale Silicon Features via 'Dip-Pen' Nanolithography and Wet Chemical Etching," *Advanced Materials*, 2 Nov 2000, vol. 12, No. 21, pp. 1600-1603.

[13]   Interview, Mirkin and DeLong with White.   Also see: Article, Seunghun Hong, et al., Northwestern University, "Multiple Ink Nanolithography: Toward a Multiple-Pen Nano-Plotter," *Science*, 15 Oct 1999, vol. 286, pp. 523-525;   Web article, David A. Bullen, Xuefeng Wang, Chang Liu and Jun Zou, University of Illinois at Urbana-Champaign and Sung-Wook Chung and Chad A. Mirkin, Northwestern University, "Development of Parallel Dip-Pen Nanolithography Probe Arrays for High Throughput Nanolithography," *Materials Research Society Symposium Proceedings*, Fall 2002, vol. 758, pp. LL.4.2.1-LL.4.2.10, at http://mass.micro.uiuc.edu/publications/papers/84.pdf as of 20 Oct 05.

funding the development of a 10,000 tip DPN array and plans for a million-plus array as well. Over the past two years, linear arrays and two-dimensional arrays have been made to cover large areas. For example, it is currently possible to make an entire silicon wafer that is nothing but pens. A commercial firm, NanoInk, based in Chicago, was established in 2002 to manufacture and market and broaden the applications of this new technology. One of the initial commercial endeavors was in the making and repair of semiconductor masks as well as Flat Panel Display repair, as well as codes imbedded in a wide range of products to ensure brand protection and integrity.[14] NanoInk has created a family of commercial products that facilitate the DPN process. The NanoInk Nscriptor™ is an integrated hardware/software lithography system optimized for the DPN process.[15] The InkCAD™ (software) and Nscriptor™ (hardware) system allows the full design, deposit, and inspection of single or multi-layered DPN patterns.[16] Another DPN-inspired company, Nanosphere, Inc., offers a commercial product to those in the life sciences industry called the Verigene™ System that automates the analysis and ultra-sensitive detection of nucleic acids and proteins.[17] These transitioned commercial applications are a direct outgrowth of AFOSR investment.

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[14] *Ibid.* Also see Article, David S. Ginger, et al., Northwestern University, "The Evolution of Dip-Pen Nanolithography," *Angewandte Chemie (International Edition),* 17 Dec 2004, vol. 43, Issue 1, pp. 31-41; Article, Ming Zhang, David Bullen, Kee S. Ryu, Zhifang Fan, University of Illinois at Urbana Champaign, and Sung-Wook Chung, Seunghun Hong, Chad A. Mirkin and Chang Liu, Northwestern University, "A MEMS Nanoplotter with High-Density Parallel Dip-Pen Nanolithography Probe Arrays," *Nanotechnology,* 12 Feb 2002, vol 13, pp. 212-217.

[15] Web article, NanoInk, Inc., "InkCAD Software Product Data Sheet, n.d., at: http://www.nanoink.net/3110_nscriptor as of 21 Oct 05.

[16] *Ibid.*

[17] Web article, Nanosphere, Inc., "Verigene System," n.d., at: http://www.nanosphere-inc.com/products as of 21 Oct 05.

The potential applications of this process are almost infinite. One of the most basic is the simple research application of trying to look at the consequences of miniaturization. That is: any time one takes a material and shrinks it down to the nanometer length scale, the material has new properties. By taking any ink and building a structure on this scale, the structure will have properties that are very different from the bulk structure. A second advantage is that one can build templates that control crystallization. Crystallization of particles, crystallization of bio-polymers, and crystallization of proteins, so, simply put, one could precisely place numerous patches on a surface to help nucleate the growth of different types of crystals that one cannot achieve through natural crystallization without a template. This is especially relevant for producing structures such as photonic band gap materials, which control the way light moves through them, as well as waveguides.[18]

In addition, this process can produce combinatorial libraries—highly miniaturized libraries of molecules that vary in composition. In the Life Sciences, combinatorial libraries are very important in terms of making DNA gene chips; making protein arrays that can be used to screen protein/protein interactions and protein small molecule interactions, which can be used to identify all sorts of new therapeutics. This could lead directly to the development of detection systems, small sensor devices that allow one to identify markers associated with many biological warfare agents. In addition to the biological warfare agent application, such nanostructures are being used to develop detection systems for deadly and debilitating diseases such as HIV, cancer, Mad Cow and Alzheimer's, long before they take hold. Dr. Mirkin, a 2004 NIH Director's Pioneer Award winner and three-time Inventors Hall of Fame Collegiate Inventor award winner, has been

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[18] Interview, Mirkin and DeLong with White; Article, Xiaogang Liu, et al., Northwestern University, "The Controlled Evolution of a Polymer Single Crystal," *Science,* 18 Mar 2005, vol. 307, Issue 5716, pp. 1763-1766.

able to develop tests that are a million times more sensitive than those currently used.[19]

Mirkin's group is currently looking at the development of nano-arrays in biology—which offers a significant improvement over the current micro-array process. This is noteworthy due to the fact that DPN allows one to manipulate biological particles including viruses, bacteria, and spores at the individual particle level. Mirkin is using this technology to understand the fundamental differences between healthy cells and cancer cells, to study how viruses infect cells, and to create new ways of selectively identifying one pathogenic agent in the presence of other similar ones. This breakthrough will open up a whole new field in molecular biology that involves single particle manipulation with DPN as the primary tool to enable that capability.[20]

In addition to the medical applications, at the other end of the spectrum is the ability to produce unbreakable cryptographic codes. Say one takes the letters "AFOSR." Information in that pattern is stored and hidden in a variety of ways. It's hidden because of its size. It's stored in the physical pattern—"AFOSR" the letters—but also the chemical composition of that pattern. So each of those letters can be made out of different types of molecules, and there could be an

[19]   Interview, Mirkin and DeLong with White; Web article, Northwestern University Chemistry Department, "Chad Mirkin Named as One of the First NIH Pioneer Reward Recipients,"   5   Nov.   2004,   at http://www.chem.northwestern.edu/news/item?item_id=2081 as of 20 Oct 05.

[20]   Interview, Mirkin and DeLong with White; Article, Ki-Bum Lee, Jo-Jung Park, and Chad A. Mirkin, Northwestern University, and Jennifer C. Smith, and Milan Mrksich, University of Chicago, "Protein Nanoarrays Generated By Dip-Pen Nanolithography," *Science*, 1 Mar 2002, vol. 295, Issue 5560, pp. 1702-1705; Article, Ki-Bum Lee, et al., Northwestern University, "Protein Nanostructures Formed via Direct-Write Dip-Pen Nanolithography," *Journal of American Chemical Society*, 18 Apr 2003, vol. 125, No. 19, pp. 5588-5589; Grant case file, "(DURINT 01) Ultrasensitive and Selective Chip-Based Detection of DNA, Northwestern University, Mirkin," AFOSR/NL, Grant No. F49620-01-0401, 15 May 01-14 May 06.

infinite number of carrier inks. In principle, one could make the "A" out of one type of ink and the "F" out of a different type, and so on. Thus DPN stores chemical and physical information in the form of the pattern, which is hidden by virtue of its size. In essence, an unbreakable code, because a unique chemical interaction key is required to read the code. That key is typically an AFM tip that measures the force of friction between tip and pattern as it is raster scanned across it.[21]

Future applications, especially in the area of national defense, are based on DPN's ability to break everything down into the most elemental components and manipulate them on the nanometer length scale. DPN designed high density circuitry that will lead to smaller weapons and space systems; the refinement of optical devices based upon colloidal crystals whereby one can control the movement of light throughout the optical system; sensors that can be used not only for bio-warfare detection but in the general area of medical and chemical diagnostics (testing and sensing); and the production of highly miniaturized and efficient battery systems. Many of the concepts and materials developed within Mirkin's laboratories under AFOSR sponsorship are now the basis for commercial detection and lithography systems.[22]

It was on 29 December 1959 that renowned physicist and Nobel laureate Richard P. Feynman delivered his famous talk entitled, "There's Plenty of Room at the Bottom."[23] In this lecture he addressed "the problem of manipulating and controlling things on a small scale, and the enormous amounts of information that can be carried or placed in an exceedingly small space." Although it took about forty years for the appropriate technology to arrive at that capability, it was the Air

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[21]   Interview, Mirkin and DeLong with White.

[22]   *Ibid.*

[23]   Web article, Richard P. Feynman, "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics," 29 Dec 1959, at http://www.zyvex.com/nanotech/feynman as of 20 Oct 05.

Force Office of Scientific Research and a talented research chemist that
ultimately made it possible.

Explosively Formed Penetrator Warheads[1]

The explosively formed penetrator (EFP) warhead concept is a derivative of the shaped charge device that evolved during the 1940's for defeating heavily armored main battle tanks.[2] The earliest published demonstration of such a device was by R. W. Wood in 1936.[3] EFP devices have been described in the literature with such phrases as Misznay-Schardin charge, end projectors, P-charge (Germany), mass focus device, self forging fragment (SFF), explosively formed projectile, or skeet warhead. For the purpose here EFP will refer to all those embodiments of the device for prosecuting the defeat of armor targets -- except the shape charge, which has come to have its own more narrow definition.

An EFP consists of an explosive charge and a metal liner (or lens). Nothing else is required to form the penetrator apart from the initiation train. But because the penetrator formation is heavily dependent upon the hydrostatic pressure build-up behind the liner, EFPs often have steel cases that increase the impulse duration from the explosive detonation. The geometry of the explosive charge is usually cylindrical with one end having a shallow concaved surface. The metal liner is geometrically matched to the concaved surface of the explosive charge. When detonated, the energy released from the explosive will accelerate and sculpt the dish-shaped liner into a high velocity projectile. The formation process

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[1] The following article was contributed by Dr. Joel W. House of the Damage Mechanisms Branch of the Ordnance Division of AFRL's Munitions Directorate (AFRL/MNMW).

[2] Book, D. Bender and J. Carleone, *Tactical Missile Warheads* [hereafter cited as *Tactical Missile Warheads*], Progress in Astronautics and Aeronautics, vol. 155 (Washington, D.C.: American Institute of Aeronautics and Astronautics), 1993, pp. 367-86.

[3] Article, R. W. Wood, "Optical and Physical Effects of High Explosives," *Proceedings of the Royal Society of London*, vol. 157, 1936, pp. 249-62.

is on the order of several hundreds of micro-seconds and the final shape is typically an aerodynamically stable contour; either a flare-stabilized "shuttle-cock" or fin-stabilized shape, although the Army has developed variants where the liner intentionally has a velocity gradient to maximize penetration at short standoffs. (Standoff describes the distance between the target and the warhead when the warhead is fired.) [4]

The earliest application for EFPs was for anti-tank mines. These devices generated hemi-spherical shaped penetrators and were relatively unsophisticated compared to the shape charge, prior to the 1970's. Their concept of employment was to defeat tank threats by perforating the undercarriage of the tank. This required limited flight stability and only modest levels of penetration performance which were attributes achieved by a hemispherical shape penetrator. [5]

During the 1960's and 1970's other technologies were developed that would impact the future of EFPs. The primary technology was the development of more powerful computers with broader utilization. Computers influenced EFP development through faster and higher fidelity modeling and simulation (M&S) capabilities. Armed with better M&S, such as the Lagrangian Elastic Plastic Impact Code (EPIC)[6] and the Eulerian Hull hydrocodes, warhead designers at the Air Force Research Laboratory (AFRL), Eglin AFB, FL, achieved new insight into the dynamics of explosive formation.[7] Initially, these continuum models were

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[4]   *Tactical Missile Warheads.*

[5]   *Ibid.*

[6]   Book, G. Johnson, Honeywell, Inc., *EPIC-2, A Computer Program for Elastic-Plastic Impact Computations in 2 Dimensions Plus Spin*, Contract Report ARBRL-CR-00373, 1978, and Report, G. Johnson, Honeywell, Inc., "EPIC-2, User Manual AFATL 1983 Version," Contract Report AFATL-TR-86-54, 1986.

[7]   Report, L. Zernon, et al., Whittaker Corporation, "Study of Long Range Armor Defeating Concepts, Vol. I: Slug Producing Warheads," Contract Report AFATL-TR-79-

limited to two-dimensional, or axi-symmetric, simulations, but quickly evolved to provide three-dimensional capability to model tactical configurations and complex penetrator-target interactions.

Computers have also impacted EFP development by use in manufacturing. Computer numerical controlled (CNC) machining gave the fabrication of proto-type designs the degree of accuracy needed for generating the irregular shapes of both the metal liner and the explosive charge. [8]

Another technology that influenced the EFP was the formulation of precision explosive charges. Formulation and process development studies at the AFRL's High Energy Research and Development (HERD) facility was instrumental in producing fine grain Octol explosive. [9] Initially this explosive was used for shaped charge applications, but it was quickly adopted for EFP designs. This precision explosive remained the benchmark melt-cast explosive fill within AFRL for over 20 years. [10]

Developing an understanding of the metal liner response in the dynamic environment of the EFP required another major area of study. Extensive physical and mechanical property characterization was necessary to improve the probability of successful projectile formation. Explosive shock, high-strain, and high-strain rate experiments were established and performed to obtain material

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77, vol I, 1979; and Report, J. Osborne, Orlando Technology, Inc., "Hydrocode Calculations of Relatively Thick Staballoy Self-Forging Fragments," Contract Report AFATL-TR-80-90, 1980.

[8] *Tactical Missile Warheads.*

[9] Memo for record, A. Beach and M. Grimmonpre, "Subject: Fine Grain Octol," n.d.

[10] Report, D. E. Lambert, S. A. Aubert and M. R. Buhler, "Characterization of Hydrodynamic Performance of AFX-235 and 65/35 Fine Grain Octol Explosives," WL-TR-96-7035, June 1996.

design information. A Split-Hopkinson Pressure Bar experiment was designed and installed for AFRL at Eglin AFB, FL.[11] This experiment provided mechanical property characterization needed at both elevated temperatures and high-strain rates. The mechanical property data was used in two ways for development of EFPs. First, the mechanical property data determined the suitability of a material for the intended application. These data were also used for the baseline acceptance tests for new lots of material. Second, the data were incorporated into the finite element design tools through constitutive models such as Johnson-Cook to improve the accuracy of M&S. [12]

These developments took place in the mid-1970's through the early 1980's. Most notable in the contribution to the development of EFPs for the Air Force, were the works of Dr. Joseph C. Foster, Jr. In 1977, Dr. Foster was presented the highest technical achievement award in the US Air Force, the Harold Brown Award, for his scientific contribution to the development of EFP technology. [13]

AFRL's Extended Range Anti-Armor Munition (ERAM) program[14] of the 1970's transitioned to production as the wide area munition, or WAM concept. It was selected by the Army for production as the M93 Hornet.[15] The munition had

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[11]   Report, R. L. Sierakowski, L. E. Malvern, and C. A. Ross, "Compression Testing of Metals at Elevated Temperatures," AFATL-TR-80-76, June 1980.

[12]   Article, G.R. Johnson and W. H. Cook, untitled, in *Proceedings of Seventh International Symposium on Ballistics* (The Hague, The Netherlands), 1983, p. 541.

[13]   Website, Office of the Air Force Chief Scientist, "Science and Technology Awards," n.d., available on the internet at https://www.st.hq.af.mil/S&TAwards.htm.

[14]   Report, W. K. Clark, "Extended Range AntiArmor Munition (ERAM) Final Report," AFATL-TR-78-128, December 1978.

[15]   Report, Yuma Proving Grounds, "M93 Hand-Emplaced Wide Area Munition (HE-WAM), Hornet Production Qualification Test," YPG-00-PQ-0125-L5XA-YPG, 06 Dec 2000.

sensor technology to detect a vehicle and to launch a skeet warhead over the target. At the appropriate height, the warhead detonated, sending an EFP toward the target. The projectile formed into a rod-shaped penetrator that perforated the top of a main battle tank.[16]

An EFP-based munition system developed for the Air Force in the 80's was the Sensor Fuzed Weapon (SFW), (CBU-97/105). SFW was the first full production EFP in the world and remains in use today. It combined a tactical munition dispenser (TMD) with a submunition, BLU-108/B, that dispensed four skeet warheads.[17] A fully loaded TMD carried forty warheads and provided an area of coverage equal in size to six (6) football fields.[18] Each warhead relied on an infrared sensor to discriminate targets along a trajectory and to provide an aim point. SFW created a force multiplying effect by engaging multiple threats with a single weapon drop over a sizeable area of the battlefield. It also represented advances in the state-of-the-art for EFPs by forming an aerodynamically stable penetrator. The precision and foundations of the earlier efforts provided improved control over the explosive formation process and, as a result, better aiming accuracy. This allowed the weapon designers to develop concepts for EFPs that could engage the target from substantial standoff distances, greater than 30 meters, and hence engage a larger area of potential targets.[19]

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[16] Website, Federation of American Scientist, "M93 Hornet [Family of Wide Area Munitions – WAM]," n.d., available on the internet at http://www.fas.org/man/dod-101/sys/land/m93.htm.

[17] Data sheet, Textron Systems Corp., "BLU-108 Submunition," 2002, available on the internet at http://www.systems.textron.com.

[18] Data sheet, Textron Systems Corp., "Sensor Fuzed Weapon," 2005, available on the internet at http://www.systems.textron,com.

[19] Website, Federation of American Scientists, "CBU-97/CBU-105 Sensor Fuzed Weapon, BLU-108/B Submunition," n.d., available on the internet at: http://www.fas.org/man/dod-101/sys/dumb/cbu-97.htm.

During the 1980's, initiation and sensor technologies were being developed that would further change the landscape for EFPs developed by the Air Force. Through the development of exploding foil initiators, or "slappers", extremely precise and relatively small-sized initiators emerged for increased design capabilities.[20] At the same time, sensor improvements were giving unprecedented amounts of information on the characteristics of the threat. It was thought possible, by the late 1980's and early 1990's, that smart weapons could have information that would discriminate classes of targets in real time, i.e., as the weapon platform approached the target.[21]

In the early 1990's work began at AFRL to exploit the size of the initiator and to use multiple initiators to change the output of the warhead. With the improved sensor technology, the warhead designer was being challenged to produce an "adaptable" or "multiple-mode" warhead. This concept munition would tailor its output to the characteristic of the target. For example, a main battle tank would be engaged at short standoff distance using a stretched-rod mode (a projectile that looked similar to that produced by a shaped charge), but at long standoff distance the warhead would function to produce an aero-stable projectile. If the target had minimal armor, say a communication van or surface-to-air missile launcher, the warhead would respond in a fragmentation mode. Determination of

[20] Report, D. Fyfe, "Feasibility Study of Selected Parameters Leading to a Pyrotechnic Delay Slapper Detonator," AFATL-TR-79-35, April 1979; Report, D. Richardson, "Slapper Detonators and Exploding Foil Acceleration Flyer Plates. Volume1. Theoretical Modelling and Experimental Results," AFATL-TR-86-63 Vol. 1, December 1986; Report, D. Richardson, "Slapper Detonators and Exploding Foil Accelerated Flyer Plates. Volume 2. Explosive Studies and Conclusions," AFATL-TR-86-63 Vol. 2, December 1986; Report, S. Smith, "Slapper Detonator Timing Evaluation," AFATL-TR-90-43, June 1990.

[21] Report, D. Lambell, et al., "Tactical Ladar Seeker Demonstration," AFATL-TR87-62, April 1988; Report, A. Legere, et al., "Tactical Ladar Seeker Technology. Phase 2," AFATL-TR-90-73, February 1991.

the final end-game strategy was left to the fire control algorithm of the on-board micro-processors. [22]

An adaptable warhead concept was demonstrated in the Anti-Materiel Sub-munitions Warhead Technology (ASWT) effort that was completed in 1997. [22] A follow-on program, Powered Low Cost Autonomous Attack System (PLOCAAS), demonstrated the integration of a flight vehicle, propulsion, laser-based radar seeker (LADAR), and an adaptable warhead.[23] This program conducted a live drop test that located and engaged a target in February of 2003.

In 1999, a new warhead effort was initiated to insert a dense metal, tantalum, into the adaptable warhead design space. This design also reduced the number of warhead modes from three, for the copper version in ASWT, to two for tantalum. [24] The design approach was to drop the use of the stretched-rod, in favor of a higher density EFP that could be fired at longer standoff distances. The greater standoff distance is a favorable characteristic for engaging a broad target area.

Future warhead attributes are being defined in AFRL's integrated concepts (ICs). For the air-to-surface mission role Area Dominance and Battle Space Access are AFRL's future visions. Both munitions system concepts exploit the use of seeker, guidance and propulsion technologies on an unmanned air vehicle (UAV) platform capable of autonomously releasing multiple submunitions. These

[22] Report, R. Tompkins and D. Manahan, Alliant Tech Systems, "Anti-materiel Submunition Warhead Technology," Contract Report AFRL-MN—EG-TR-1998-7062, July 1998.

[23] Report, Office of the Inspector General, Department of Defense, "Powered-Low Cost Autonomous Attack System Advanced Technology Demonstrator," Report No. D-2001-106, Audit Report, May 2001.

[24] Report, E. Volkmann, AFRL/MN, "Tantalum Warhead Technology Final Report," Contract #, F08630-99-C-0091, n.d.

submunitions will have robust kill mechanisms (jetting rod, EFP, fragmentation, blast, etc.) to defeat both fixed and mobile ground targets. The development of these next-generation warhead concepts are challenging the warhead designer paradigm to innovate small, but highly lethal warheads that can more efficiently couple their energy output to the intended target. [25]

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[25] Briefing, M. Duval, "Munitions Directorate Integrating Concept (IC) Technology Planning Overview," 24 Oct 2005.

Fly-By-Wire Flight Controls

Fly-by-wire (FBW) is defined as a flight control system wherein vehicle control input is transmitted completely by electrical means. Since the Wright Brother's first Flyers, pilots have controlled their aircraft by pulling on levers, yokes, sticks, or pedals, which transmitted the pilot's inputs to the control surfaces at first through purely mechanical means like cables and pulleys, then later through hydraulic actuators when larger, faster, and more complex aircraft outpaced the pilot's brute strength and ability to control the aircraft, which was especially difficult, if not impossible, in the new regions of transonic and supersonic flight. Fly-by-wire offered the potential advantages of high-speed and high-fidelity transmission of command inputs; easy installation and maintenance; easy pilot operation; no regular adjustments; and considerable reduction in size and weight. Fly-by wire proposed to change the aircraft control paradigm of a statically stable aircraft mated to cable controls that was universal since the dawn of controlled flight. In the case of most paradigm shifts, the process was neither easy nor obvious.[1]

The path to fly-by-wire came at the intersection of two related technologies: aircraft stability control and aircraft flight controls. The former refers to systems that actively stabilize an aircraft without the pilot's direct intervention. The latter includes systems that translate the pilot's active input from a stick to the aircraft's control surfaces. The first imposition of electrical devices on the mechanical systems came during World War II. Engineers devised an autopilot system for heading and attitude stabilization to improve bombing accuracy, which was also used in conjunction with the famous Norden bomb sight. After the war, electron tubes and magnetic amplifiers increased the control capabilities of the autopilot

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[1] Article, James E. Tomayko, "Blind Faith: The United States Air Force and the Development of Fly-By-Wire Technology" [hereafter cited as "Blind Faith"], in Book, ed. by Jacob Neufeld, et al., *Technology and the Air Force: A Retrospective Assessment*, (Washington, DC: Air Force History and Museums Program), 1997, p. 163.

systems. By the mid-1940s, hydraulically boosted controls supplanted aerodynamically boosted controls for the higher-speed aircraft like the new jet-powered F-80 and F-86. This system evolved into fully powered hydraulic controls that provided a greater degree of separation between the control stick and the control surface. Because of that separation, the new hydraulic systems required a means for artificial feedback ("feel") to the pilot. By the early Cold War, fully hydraulic controls became standard on all new aircraft.[2]

In 1955, the Air Force imposed a reorganization on its laboratory systems that resulted in, among other things, the creation of a new Flight Control Laboratory (FCL). This new lab brought "together specialists from other laboratories in all elements of control systems, including aerodynamics, mechanical design, control theory, and instruments." One of the first actions of its commander was to start a long-term program that eventually resulted in the development of fly-by-wire. The current abundance of new aircraft (and spacecraft) under development or in the planning stages offered ample opportunity for the FCL engineers to improve the flight controls state of the art. They were aided in their endeavor by the advent of greatly improved electronics and nascent computers. Those two new technologies were both a blessing and a curse: they enabled electrical aircraft control, but threw up a huge mental barrier in the minds of the aeronautical community, especially the military, because of their notorious unreliability. The earliest fly-by-wire programs had to not only develop the electrical controls and computers, but also prove that

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[2]   Paper, Systems Engineering Group, "Progress in Flight Control Technology," Oct 65; Book, William Elliott, AFMC/HO, *The Development of Fly-By-Wire Flight Control* [hereafter cited as *Development*], AFMC Historical Study No. 7 (WPAFB, OH: AFMC History Office), Dec 1996, pp. 1-7; Rpt, Vernon R. Schmitt, James W. Morris, and Gavin D. Jenney, "Fly-By-Wire Research and Development by the Air Force Flight Dynamics Laboratory" [hereafter cited as "Fly-by-Wire"], March 1996, pp. 4-8.

electronics could replicate the reliability, and feel, as well as the function, of their mechanical counterparts.[3]

During the latter 1950s, both the FCL and the aerospace industry had some cognizance of fly-by-wire's potential, but continual problems with electronics prevented that potential from being reached. As such, the government labs mostly acted as observers of external fly-by-wire research in the private sector and at NASA for its spacecraft. The Air Force Flight Dynamics Lab (FDL) did experiment with a system for the X-20 Dyna-Soar during that period, however. In 1963, the Air Force folded the Flight Controls Lab back into the Flight Dynamics Lab. Two years later, the FDL decided to coalesce its FBW research into a flight test program. It was informally called the B-47 In-House Program and ran from August 1966 to November 1969. The FDL chose the B-47E *Stratojet* for its FBW testbed because it had plenty of room for the system, had two pilots, its size meant it could benefit from FBW, and one was readily available for testing. The program proceeded in phases, the first of which had only pitch controlled via fly-by-wire. This configuration first flew on 14 December 1967, making it the first Air Force aircraft to fly using fly-by-wire controls, with the caveat that it was not a 3-axis system. It was justifiably deemed the first aircraft from the above list to demonstrate fly-by-wire flight controls. Later flights incorporated roll axis control, but yaw controls were never part of the program. The engineers and pilots were greatly encouraged by the success of this FBW system, which established the FDL as a world leader in this technology and led to follow-on efforts at the FDL and elsewhere.[4]

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[3] Book, Squire Brown, *A Genesis Workshop* [hereafter cited as *Genesis*], (WPAFB, OH: ASC/HO) 2003, p. 61; "Blind Faith," pp. 166-167.

[4] "Blind Faith," 167-172; *Development*, pp. 11-17; *Genesis*, p. 61; "Fly-by-Wire," pp. 25-40; Book, James J. St. Peter, *The Heritage of the Flight Dynamics Laboratory* [hereafter cited as *Heritage*], (WPAFB, OH: Flight Dynamics Lab), Oct 1988, pp. 25-26.

This success led to the application of fly-by-wire to the F-4 Phantom under the Survivable Flight Control System (SFSC) program in 1968, which was a product of combat experience in Vietnam showing the susceptibility of mechanical systems to enemy fire and to the pending development of several new fighters in the early 1970s. Fly-by-wire for the F-4 Phantom had been investigated by Mc Donnell Aircraft employees since the late 1960s. They had flight tested control augmentation and stability augmentation systems by 1968. At that point, however, they had developed two fly-by-wire configurations and built hardware, but neither system had flown. The Flight Dynamics Lab's SFCS was predicated on the idea that an electrical fly-by-wire system offered a higher degree of survivability. Their intent from the beginning was to modify an F-4. The test aircraft, Tail No. 62-12200, was a YRF-4C and received the new YF-4E designation. The system as installed included: side-stick controllers for front and back seat, though the center stick was retained to operate the redundant mechanical controls; quad-redundant analog computers; and fly-by-wire controls for all three axes. Pitch and yaw cables were initially retained, but eventually removed when pilots developed confidence in the system. On 29 April 1972, this aircraft flew from Lambert Field in St. Louis. Because of that flight, this aircraft earned the honor of being the Air Force's first all fly-by-wire (about 3-axes) aircraft, with the caveat that mechanical backup systems were still in place for pitch and yaw. On 22 January 1973, the same aircraft made its first fully-fly-by-wire (3 axes, with no mechanical backups) flight. NASA had considerable expertise in this regard, as all its manned spacecraft had been fly-by-wire for the past decade. The result was the first practical fly-by-wire system, which was immediately incorporated into the YF-16. It should be noted that NASA was running a very similar program involving the F-8 Crusader, which flew about a month after the FDL's F-4.[5]

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[5] *Development*, pp. 18-21; "Blind Faith," pp. 175-180; "Fly-by-Wire," pp. 78-80; Rpt, Air Force Systems Command, "Development Plan Advanced Development Program 680J: Survivable Flight Control System (SFCS)," 1 Apr 70. For more on the F-8 program see: Proceedings, NASA, *Proceedings of the F-8 Digital Fly-By-Wire and Supercritical Wing First Flight's 20th Anniversary Celebration, NASA Dryden Flight*

The F-16 was the first Air Force aircraft to be designed with fly-by-wire flight controls, thus its nickname "The Electric Jet." This was regarded as a high-risk design at the time, but proved to be a key to General Dynamics winning the Light Weight Fighter (LWF) program over the YF-17, which later became the F-18 (after incorporating a digital fly-by-wire flight control system). The F-16's system used an analog computer and full, 3-axis FBW to control its "relaxed static stability" design. The first prototype flew on 2 February 1974. One extreme example of the capabilities imparted by FBW flight controls was the X-29 forward-swept wing demonstrator aircraft. The X-29, while not a first in terms of FBW technology, was an example of the advantages conferred by FBW. It was designed to be nearly neutrally stable in the supersonic region to minimize drag, but became highly unstable transonically and subsonically. These characteristics dictated the use of a computerized fly-by-wire flight control system capable of stabilizing the aircraft. The X-29 advanced technology demonstrator began flight testing on 14 December 1984. Now, the most modern aircraft in the world – such as the F-117, B-2, Boeing 777, and Unmanned Combat Air Vehicle – all use fly-by-wire flight control systems.[6]

Research Center, Edwards AFB, California, 27 May 1992, Vol. I, NASA CP-3256, 1996, esp. pp. 1-53.

[6]   *Development*, pp. 22-33; "Blind Faith," pp. 179-183; *Heritage*, pp. 223-226.

Free-Fall Parachutes and Ejection Seats

Near the end of World War I, military planners generally conceded the necessity of using parachutes to escape from damaged airplanes. Most early parachutes were of the *attached type,* in which the parachute container was fastened to the fuselage of an airplane, the basket of a balloon, or the car of an airship. The harness of the jumper was connected by a life line to the shroud lines of the parachute. Mechanics closed the container with string that was strong enough to hold the parachute in place during normal flight. As the jumper dropped away, or bailed out, however, his or her weight would break the string, thus allowing the chute to run freely into the air. This attached type of parachute, primarily designed for jumping from balloons, was soon found, however, to be unsuitable for use by the crew of airplanes. Special provision within the airplane had to be made for carrying the chute. The life line could come to the aviator's harness on one side of the airplane only, and aviators had found getting out of the aircraft on the outside of a spin practically impossible. In the case where an aircraft entered a vertical nose dive with the wings gone, the fuselage could possibly attain greater sped than the crewman, thus making it impossible for him or her to break the chute free from its container. Finally, the long life line could get caught on some part of the disabled airplane.[1]

Personnel at McCook Field observed first hand an example of the last-named difficulty in the fall of 1919, when Lieut. R. A. Caldwell of the British Royal Flying Corps went up in a De Havilland airplane to demonstrate the "Guardian Angel," a parachute designed specifically for aircraft pilots by retired British engineer Richard Everard Calthrop. Caldwell was killed when his life line caught on the rocker arm of the elevator control cables of the airplane and thus caused a free drop of several hundred feet. Caldwell's accident emphasized the necessity

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[1]   Web page, Master Sergeant Edwin H. Nichols, Chanute Field, Rantoul, Ill., "Parachute—A Friend in Need," *U.S. Air Services,* July 1924, pp. 32-34, available on the Internet at http://www.au.af.mil/au/aul/school/sncoa/bott.htm on 18 Oct 05.

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of developing a *free type* parachute with a manually operated freefall rig that could be operated by a jumper after falling clear of a disabled aircraft.[2]

Such a need had already been recognized by Major Edward L. Hoffman, chief of the Equipment Section at McCook Field, and was probably why in January 1919 he placed James Floyd Smith (1884-1956), a veteran flyer and jumper, in charge of the section's Parachute Branch. Smith and his wife Hilder made their first parachute jumps in 1914, but after Hilder's second jump ended in near disaster, he began considering how the design of parachutes could be improved. A year later, as a test pilot for Martin, he established three world records for altitude using a Martin S plane over San Diego. In 1917 Smith made the first simulated carrier landings at North Island. After the United States entered World War I, he was appointed chief pilot in charge of final acceptance inspection of De Havilland biplanes at McCook Field. Soon thereafter, in 1918, Smith took out a patent on a free manually operated parachute pack. This Model A parachute was 28 feet in diameter with a 42-inch patent, shock-absorbing vent. Each of its 30 shroud lines had a breaking strength of 80 pounds. In designing the parachute, Smith was assisted by Guy Ball, a branch employee, and Leslie J. "Sky-Hi" Irvin (1895-1966), a veteran stunt jumper and parachute manufacturer. The latter apparently played a significant role in the design of the backpack, for two years later he received a patent for "improvements in safety parachute pack device," most likely the chute container worn on a body harness. Although many Army officials were reluctant to equip pilots with an extra 25 pounds of parachute weight that might possibly save their lives, Air Service deputy commander Brig. Gen. Billy Mitchell, who at this time was beginning to advocate using parachutes for a new corps of assault troops dropping from airplanes, and Major Rudolph William Schroeder, chief test pilot at McCook Field, interceded and ordered that Smith make up several samples for practical demonstrations of the device.[3]

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[2]   *Ibid.*

[3]   Web page, Major E. L. Hoffman, Chief, Equipment Section, McCook Field, "Directions for the Operation of the Adopted Type of Parachutes and Comments

Following eleven dummy drops of the parachute-and-backpack combination, the first live drop test of the device was made on 28 April 1919. On that day Smith piloted a De Havilland DH-9 plane up to an altitude of 1,500 feet. After Smith throttled the plane, which at the time was moving at a speed between 80 and 100 miles per hour, Irvin jumped out of the plane. After falling for a couple of seconds he pulled a circular ripcord ring handle from a harness-mounted pocket located over his right breast. Within one and two-fifths seconds the canopy streamed out and filled. The descent went well, although Irvin broke an ankle when a wing gust swung him into a hard landing. Irwin's jump, the first ever made by a person with a free-fall parachute, was followed within a month by jumps by Smith (who fell more than 500 feet before pulling his ripcord), parachute mechanics James Russell and James Higgins (who had never jumped before), and, on 19 May 1919, Army Sergeant Ralph W. Bottriell (who had already made more than 200 leaps before joining the air service in 1909). Major Schroeder was the first Air Service aviator to wear the Smith parachute. This Model A parachute, for which Irvin's manufacturing company received an initial

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Thereon" [hereafter cited as "Directions"], U.S. Air Service, Dec 19, pp. 18-19, available on the Internet at http://www.au.af.mil/au/aul/school/sncoa/bott.htm on 18 Oct 05; Web page, Waldo Waterman, President, the Early Birds of Aviation, "James Floyd Smith 1884-1956," *The Early Birds of Aviation Newsletter*, 18 Dec. 1962, available on the Internet at http://www.earlyaviators.com/esmithfl.htm; Web page, Henry Serrano Villard, "Biographical Notes [on Rudolph William Schroeder]" from his book *Blue Ribbon of the Air* (1987), available on the Internet at http://www.carlyaviators.com/eschroed.htm on 17 Oct 05; Web page, Jim Bates, "Parachuting Milestone: Freefall" [hereafter cited as "Parachuting"], *Aerial Delivery*, 8 Oct 05, pp. 13-14; Web page, USAF Museum, "Early Frec-Fall Parachute," n.d., available on the Internet at http://www.wpafb.af.mil/museum/history/postwwi/effp.htm on 18 Oct 05. For a diagram of the parachute, harness, and backpack combination that accompanied Smith's patent application, filed on 27 July 10 and issued on 18 May 20 (U.S. patent no. 1,340,423), see Web page, n.a., "The Modern Parachute," n.d., part of the Ohio Academy of Science's "Heartland Science: Ohio's Legacy of Discovery & Innovation" web site, available on the Internet at http://www.hcartlandscience.org/aeroav/parachute.htm on 18 Oct 05.

order of 300 only a few days after his jump, evolved into a Model S parachute assembly that was used for many years.[4]

Airmen used a manual bail-out method for escaping from a disabled aircraft during the 1920s and 1930s and World War II. The advent of faster fighter aircraft, however, made it clear that pilots would need assistance in getting out of them. In May-June 1945, as World War II ended in the European theater, Col. Randy Lovelace and Lt. Verner Wulff of the Aero Medical Research Laboratory (AMRL), (a predecessor organization of AFRL's current Human Effectiveness technology directorate) and Dr. Edward J. Baldes of the Mayo Aero Medical Unit traveled to England, Germany, and Sweden to obtain scientific and technical data on European ejection seats that had been developed during the conflict. AMRL personnel initiated an ejection-seat research program, under the direction of Major Harvey Savely, in July 1945. Under the supervision of Baldes, the Allis Chalmers Company in three weeks constructed a 30-foot-high testing tower, which was adjustable up to 30° aft of the vertical. The Army Material Command's Frankford Arsenal in Philadelphia provided a T-2 telescoping catapult that extended from 36 to 60 inches. Using a half charge of powder and a reproduction of a German ejection seat, AMRL personnel made the first (albeit unsuccessful) attempt at ejection-seat firing in the United States on 11 October 1945. The first two human ejections were conducted on the tower in November 1945. The seat accelerations were 11g, and the subject accelerations were 20 g on the hips, 15g on the head, and 10g on the shoulders.[5]

AMRL personnel then began testing, with dummies, a seat and catapult system in a modified P-61B Black Widow at Wright and Muroc fields. This system was designed to allow a pilot (or another crew member) to squeeze a

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[4]   "Directions," pp. 18-19; "Parachuting," p. 14.

[5]   Book, Charles A. Dempsey, *The Air Force Aerospace Medical Research Laboratory: 50 Years of Research on Man in Flight* [hereafter cited as *50 Years*], (WPAFB, Ohio: Aerospace Medical Research Laboratory), 1985, pp. 33 and 51-52.

trigger that initiated a series of events that would eject him from a disabled plane, separate him from his seat in mid-air, and then cause a parachute to open automatically and allow him to land safely on the ground. The seat would be ejected by means of a gun attached to the seat back by a long tube that filled the gun barrel (only 38 inches long due to limited space in the cockpit) like a projectile. As the gun fired a 37 mm cartridge, the gun barrel would stretch (like a telescope), allowing the force of the powder explosion to be less but still obtain enough distance for the pilot to clear the fuselage of the plane. During this ejection the seat would be accelerated almost instantly to a speed of about 60 feet per second, or 40 miles per hour, causing a strain of about 10 g on the pilot. Three seconds later, a time mechanism would explode another small cartridge that would release the strap holding the pilot to the seat and open a small parachute attached to the seat that would pull it away from the pilot. As the seat began to separate, it would pull a rip cord attached to a Quilter Timer Parachute Opener, which three seconds later would activate a cartridge that would automatically open the pilot's parachute.[6]

The first live test of the system occurred on 17 August 1946, when pilot Capt. J. W. McGuyrt flew the P-61B up to an altitude of 6,000 feet and then maintained a speed of more than 300 miles per hour over Patterson Field. At 1,200 feet First Sgt. Lawrence Lambert, a 29-year-old test jumper in the Wright Field Personal Equipment Laboratory's Parachute Branch who had made 58 previous jumps, activated the system, which allowed him to clear the tail fin of the airplane by about 20 feet and subsequently land in a field in the town of Osborn (later Fairborn). The first American to be successfully ejected from an aircraft, Lambert on 9 April 1947 was awarded the Distinguished Flying Cross for "his courageous

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[6] Web page, Public Relations Office, Air Material Command (AMC), Wright Field, untitled [press release on Lambert's ejection-seat jump], Aug 46, available on the Internet at http://afehri.maxwell.af.mil/Documents/pdf/lambert.pdf on 18 Oct 05. The press release claims that an AMC laboratory developed the Quilter Timer, but the device's name would seem to indicate that it had actually been invented by British parachute manufacturer Raymond Quilter.

action in the face of unknown factors that might have caused serious injury or loss of life." Capt. Vincent "Vinny" Mazza of AMRL made the first ejection-seat escape from a jet aircraft (a specially modified TF-80C Shooting Star), over San Pablo Bay in California on 31 May 1949.[7]

Following additional design and testing of various ejection seats by individual aircraft contractors in the 1950s and 1960s, the AMRL and the Aeronautical Systems Division's Life Support Program Office between 1968 and 1975 jointly managed the development of a new, standardized unit called the Advanced Concept Ejection System II (ACES II). First flown in an A-10 Thunderbolt II from Fairchild Republic Company's plant in Farmingdale, N.Y., in April 1978, it has also been used in various forms in the F-15 Eagle, F-16 Fighting Falcon, F-117 Nighthawk, and F-22 Raptor fighters, and the B-1B Lancer and B-2 Spirit bombers. The system uses a controlled-force catapult, a sustainer rocket, and a gyro-stabilized vernier pitch-control rocket to assure safe ejections from a wide variety of emergencies while minimizing the probability of injury due to ejection forces, seat tumbling, or parachute-opening shock.[8]

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[7]   *Ibid.*; Web page [memo], Col. C. K. Moore, Chief, Aircraft Laboratory, Aircraft & Physical Requirements Subdivision, Engineering Division, Wright Field, to Commanding General, AMC, "Recommendation for the Award of the Distinguished Flying Cross to First Sgt. Lawrence Lambert," 29 Aug 46, available on the Internet at http://afehri.maxwell.af.mil/Documents/pdf/lambert.pdf on 18 Oct 05; Web page, n.a., "Chairborne Delivery," *Time,* 2 Sep 46, available on the Internet at http://www.time.com/time/archive/printout/0,23657,803904,00.html on 13 Oct 05; Book, ASC/HO, "Development of High Speed Escape Methods" sidebar, p. 109 in *Splendid Vision, Unswerving Purpose: Developing Air Power for the United States Air Force during the First Century of Powered Flight* [hereafter cited as *Splendid Vision*], (Wright-Patterson Air Force Base, Ohio: Air Force Material Command), 2002; Web page, USAF Museum, "Ejection Seat Development," n.d., available on the Internet at http://www.wpafb.af.mil/museum/history/postwwii/esd.htm on 13 Oct 05.

[8]   *Splendid Vision*, p. 109; *50 Years,* pp. 167-168.

GPS Guided Munitions[1]

During Operation Iraqi Freedom the promise of precision weaponry was finally realized. With precision, the Air Force was able to fulfill the dreams of the early aviation pioneers: that an air force would be able to achieve sweeping strategic effects and be the pre-eminent force on the battlefield. [2]

The road to precision required an enormous investment in technology combined with a complete transformation in the conventional philosophy of bombing. The final breakthrough that made precision a reality occurred with weapons that use the Global Positioning System (GPS), because GPS provided inexpensive, all-weather, and extremely precise engagement. GPS guided munitions have transformed and expanded the role of bombers. With long on-station times and large payloads of GPS guided weapons, the bomber provided on-call, close air support to ground forces in operations in Afghanistan.[3] This paper presents a concise history of GPS guided munitions, the latest improvements to the technology, and future trends in the development of weapons to provide precision, all-weather effects.

The introduction of the first laser guided bomb (LGB) in 1968 marked the beginning of the evolution of precision munitions. Use of the LGB in Vietnam during the Linebacker operations clearly illustrated the ability to reduce sortie

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[1]   The following article was contributed by Mr. Steven G. Stockbridge and Mr. Robert A. Murphey, both of the Guidance Navigation and Control Branch of the Advanced Guidance Division of AFRL's Munitions Directorate (AFRL/MNGN).

[2]   Article, Lt Col David K. Edmonds, USAF, "In Search of High Ground, the Airpower Trinity and the Decisive Potential of Airpower" [hereafter cited as "In Search of High Ground"], *Aerospace Power Journal*, vol. 12, no. 1, Spring, 1998.

[3]   Book, Andrew F. Krepinevich, *Operation Iraqi Freedom: A First-Blush Assessment*, Center for Strategic and Budgetary Assessments (Washington, D.C.), 2003, pp. 26-7.

rates while increasing the likelihood that difficult targets, like bridges and tanks, could be destroyed.[4] Although shown to be highly accurate, environmental and operational constraints kept the LGB and later precision weapons, like the guided bomb unit (GBU-15) and air-to-surface ground missile (AGM-65) guided bombs from widespread use over the next two decades. Indeed, in 1991, only five percent of the bombs dropped in Operation Desert Storm were precision guided bombs.[5] In addition to small stockpiles of these weapons, many opportunities for using smart weapons were lost due to restrictions in weather. Furthermore, few coalition aircraft were equipped to use precision guided munitions. Even as late as 1995, during Operation Deliberate Force, only the U.S., Britain, and France possessed aircraft capable of using precision weapons and even then, US aircraft delivered 622 of the 708 total precision weapons employed.[6] The conflicts of the early 1990's clearly underlined a pressing need for low cost all-weather, precision, direct attack munitions.

GPS brought unprecedented all-weather navigation accuracy and day/night capability with worldwide availability. Engineers at the Air Force Armament Laboratory (AFAL), currently the Air Force Research Lab Munitions Directorate (AFRL/MN), recognized the potential of GPS technology and envisioned the development of a new class of precision tactical munitions that integrated a GPS receiver with a tactical grade inertial sensor system. However, the realization of that vision was far from straightforward. A long line of development projects, beginning in 1976, produced many incremental capabilities. First, GPS alone would not be sufficient for guiding missile and munitions. Missile body rates and

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[4]   Book, Benjamin S. Lambeth, *The Transformation of American Air Power, A Rand Research Study* (Ithaca and London: Cornell University Press), 2000, p. 11.

[5]   Article, Grant T. Hammond, "Myths of the Gulf War: Lessons Not to Learn," *Air Power Journal*, vol. 12, no. 3, Fall 1998.

[6]   Article, Lt Col Mark J. Conversino, "Executing Deliberate Force, 30 August – 14 September 1995," *Deliberate Force: A Case Study in Effective Air Campaigning*, ed. by Col Robert C. Owen (Maxwell AFB, AL: Air University Press), 2000, p. 164.

accelerations were still needed for accurate guidance and the GPS navigation solution, provided in a geodetic frame, was incapable of delivering this inertial information. However, the state-of-the-art inertial measurement sensors were large and expensive, – clearly not suited for munitions applications. Gyroscopes were needed that did not rely on large, costly and fragile gimbals. And so the Air Force Armament Laboratory and Draper Laboratory began work on the ring laser gyroscope (RLG) in 1976 which culminated in 1986 with a prototype of the first missile-sized, tactical grade three-axis RLG sensor. It wasn't long before tactical inertial navigation systems (INSs) based on the RLG began showing up in weapons like the AGM-130, and Conventional Air Launched Cruise Missile. By 1995, work at the Air Force Armament Laboratory had led to the first tactical-sized fiber optic gyro (FOG) prototype. With its smaller size and increased reliability, the FOG promised to effectively replace the RLG for tactical applications.[7]

Meanwhile work on placing a GPS receiver in a weapon was slowly proceeding. As it turns out, GPS is the perfect companion for optical gyros as their error sources are completely uncorrelated. In a combined navigation filter, the GPS can calibrate out the errors in the inertial sensors. The use of GPS also makes alignment of the inertial sensors much simpler. The inertial sensor can be aligned while in flight instead of being held stationary on the runway. The first missile-class GPS receiver was placed on a weapon in 1992 as part of the Operational Concept Demonstration (OCD) effort at the now renamed Armament Directorate, previously the Air Force Armament Laboratory.[8] The OCD consisted of a Collins INS and Collins fast acquisition GPS receiver installed on a GBU-15.

[7] Technical report, Ren-Young Liu, Tamim El-Wailly, Matt Olsen, and Gary Adams, "Fiber Optic Gyro (FOG) Inertial Measurement Unit (IMU)," WL-TR-97-7017, Defense Technical Information Center (DTIC) Accession Number ADB224230, 1997.

[8] Article, S. Snyder, L. Tellman, P. Torrey, and S. Kohli, "INS/GPS Operational Concept Demonstration (OCD) High Gear Program," *Aerospace and Electronic Systems Magazine, IEEE*, vol. 9, issue 8, Aug 1994, pp. 38-44.

The INS-GPS units were integrated with a Honeywell flight computer and placed in the GBU-15's seeker housing. The GBU-15 airframe, and that of other weapons for that matter, presented a problem for GPS receivers. The skid-to-turn maneuver used in guidance can lead to high angles of attack and make it difficult to ensure visibility of a sufficient number of satellites by the GPS antenna. To ensure that at least 3 satellites were visible at all times, two antennas were placed on the weapon - one in front of the forward strakes and the second behind the tail. OCD flight tests in February of 1993 clearly showed great potential with all-weather navigation errors at less than 8 meters. The OCD development eventually led to the production in 1997 of the first affordable precision guided weapon, the Joint Direct Attack Munition (JDAM). By the beginning of 2005, a large assortment of weapons have integrated GPS-INS navigation, including upgrades to the older GBU-15, AGM-130, AGM-65, Conventional Air Launched Cruise Missile, and Tomahawk Cruise Missiles, and also newer generation weapons designed specifically to exploit GPS including the Joint Stand Off Weapon (JSOW), Joint Air to Surface Stand Off Missile (JASSM), Wind Corrected Munitions Dispenser (WCMD), and the Small Diameter Bomb (SDB).[9]

No sooner had the Air Force demonstrated the potential for GPS navigation on weapons, it began to consider how to make it more robust to obvious countermeasures, specifically, jamming. The signal from GPS satellites is extremely weak, making it very susceptible to jamming (intentionally or not) by a signal in the same frequency band. In 1991 the Armament Directorate began the Tactical GPS Antijam Technology (TGAT) effort to explore antijam (AJ) methods of designing GPS-INS navigation systems. In the following six years AJ technologies included beam steering, whereby the antenna is electronically pointed toward the GPS satellites; null steering, where the antenna is electronically steered away from jammers; and combinations of spatial and

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[9] Web journal, D. Lennox, Ed., *Jane's Air-Launched Weapons*, Jan 2006, available on the internet at http://jalw.janes.com/public/jalw/index.shtml.

temporal processing, where nulls and beams are created dynamically both in space and in time. In 1998 the Munitions Directorate demonstrated the first fully integrated GPS/INS weapon on a JDAM, beginning a new era for precision guided weaponry.[10]

The onset of the new millennium brought continued advancement of AJ technologies. Ultra Tight Coupling (UTC), where the GPS and INS navigation filters are dynamically coupled in a single navigation filter, showed a significant increase in jamming immunity. Space Frequency Adaptive Processing (SFAP), and Space Time Adaptive Processing (STAP) further increased both the AJ margin while increasing the precision of the navigation solution and making the fabrication of AJ-GPS-INS navigation units much more affordable. In the next few years these technologies will ensure that the threat of white noise GPS jamming has been effectively eliminated.[11]

New threats are certainly not out of the question and so new technologies for improving GPS weapon guidance are being examined. In the extreme case that an enemy is able to disrupt the GPS signal in space or destroy our satellites, methods for obtaining GPS-like precision without GPS are being considered. These GPS alternatives would utilize the improved GPS constellation as much as possible but could switch to optical and radiometric sensors and processing to augment the navigation solution when GPS is denied.[12]

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[10]   Technical report, G. Diemond, M. Fisher, and J. McMullan, "Tactical GPS Antijam Technology," WL-TR-94-7074, DTIC Accession Number ADB199201, Oct. 1993; Technical report, A, Auteri, R. Briones, R. Cantwell, S. Howard, M. Kimmitt, S. Manfanovsky, E. Perdue, E. Reilly, and G. Taylor, "Tactical GPS Antijam Technology," WL-TR-94-7077, DTIC Accession Number ADB197307, May 1994.

[11]   "In Search of High Ground."

[12]   *Ibid.*

The full impact of GPS guided munitions was realized in Operations Enduring Freedom and Iraqi Freedom. In World War II, 70 out of every 500 bombs fell within 1,000 feet of the target. Today one B-2 can simultaneously release 80 MK-82 JDAMs, each independently targeted, in any weather, with an accuracy unimagined by WWII mission planners. Today's inventory of GPS guided weapons owe much to the pioneering AFAL programs, which provided the required knowledge and experience in government and the contractor community to insure their current success.[13]

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[13]   *Ibid.*

Ground-Based Laser: Shootdown of an Aerial Target

The Air Force Weapons Laboratory (AFWL) succeeded in the first-ever shootdown of an aerial target by a ground-based laser on 14 November 1973. Project DELTA, or Drone Experimental Laser Test and Assessment, tested an integrated system consisting of the field test telescope (FTT) tracker-imager and a carbon dioxide gas dynamic laser (GDL). Results demonstrated the system could track a target, in this case an Army drone with a fuel tank that resembled that of an F-4 Phantom fighter aircraft, and point and deliver a laser beam accurately and precisely on target. The 7.62-centimeter diameter beam deposited sufficient energy on target to cause the drone's fuel tank to explode. Although DELTA was a major technical milestone whose true value was to elevate confidence in the development of laser weapons, it had begun as virtually an afterthought to the development of the Air Force's Tri-Service Laser or TSL.[1]

With the invention of the laser in 1960, the Air Force immediately began assessing the use of lasers as a potential weapon system. In a short time, the Air Force Special Weapons Center, and its follow-on descendent, the Air Force Weapons Laboratory, began pursuing the goal of an airborne laser. Initially, two major component systems would need to be developed, and then integrated. First, the lab needed a laser that was powerful enough to deliver large amounts of energy in a highly focused beam to a small target area. Second, the system had to be capable of acquiring and tracking the target, and then point the laser beam at the target. After a period of intense research, the Air Force determined the best type of laser would be the CO_2 gas dynamic laser or GDL. DoD's

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[1]   Book, Robert W. Duffner, *Airborne Laser: Bullets of Light* [hereafter cited as *Airborne Laser*], (New York: Plenum Press), 1997, pp. 39-40; Interview, Dr. Robert W. Duffner, AFWL/HO, with Lt Col Thomas J. Dyble, USAF, Space Technology Center, 1 Aug 1988; Film, AFWL, "Project DELTA," 14 Nov 1973.

Advanced Research Projects Agency (ARPA) wanted to concentrate research on a single Tri-Service Laser (TSL) and coordinate it under AFWL.[2]

In early 1969, AFWL contracted with AVCO-Everett Research Laboratory to build a high-energy GDL laser. However, AVCO did not meet all the technical specifications to complete the TSL. In 1972, AFWL accepted the flawed TSL, confident that its own scientists could correct the TSL in order to ultimately generate the desired laser beam. Indeed, in early 1972, AFWL's troubleshooting team conquered the engineering integration obstacles to produce a high quality, high-power laser beam. Concurrently, in early 1969, AFWL contracted with Hughes Aviation to develop an acquisition, pointing, and tracking system called the field test telescope (FTT). Delivered to AFWL in October 1970, the FTT successfully tracked a T-39 aircraft and then hit the aircraft target with a low-power laser beam in flight. [3]

The next stage was to integrate the two component systems. AFWL assessed two performance functions of the integrated system. First, could the imaging sensors on the FTT accurately identify a vulnerable aimpoint on the target for the laser beam to strike, and second, could the focused beam precisely hit the target so the aimpoint was squarely in the center of the beam footprint? In pursuit of these goals, AFWL scientists safely and gradually increased the power from the TSL to the FTT, and successfully directed a 100-kilowatt, 10.6-micron CO_2 laser beam at both static and moving targets for 3 seconds without damaging either the FTT or the TSL. The system was first tested on stationary

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[2] *Airborne Laser*, pp. 13-20; Rpt, n.a., "Advanced Development Plan: Gas Dynamic Laser Weapon," WRLE-67-170, Sept 1967, pp. A-1—A-2; Book, John D. Anderson, Jr., *Gas Dynamic Lasers: An Introduction* (New York: Academic Press), 1976, p. 2.

[3] *Airborne Laser*, pp. 25-32; Interview with Dyble, 1 Aug 1988; Interview, Duffner with Col John C. Rich, USAF, Retired, 10 Jan 1989; Rpt, Col Robert W. Rowden, AFWL/CC, "AFWL Significant Events," 31 Dec 1971.

targets at various ranges at Kirtland Air Force Base's Starfire Optical Range. Then in December 1972, AFWL wanted to find if the device could hit a moving target. Technicians mounted the target, roughly the size of a wallet-sized photo, on a 30-foot rotoplane. The rotoplane, resembling a windmill, rotated the target 360 degrees perpendicular to the ground at 25 revolutions per second. The FTT pointed the laser beam to hit the rotoplane moving target at over a mile away, holding the beam on target for several seconds to confirm pointing and tracking accuracies. This was a "laser first" and a tremendous accomplishment for AFWL's scientific staff.[4]

Following the success of the integrated TSL/FTT device, some members of the Airborne Laser Laboratory (ALL) team thought that rather than going directly to installing and testing the device on an aircraft, a ground-based shootdown of an aerial target was the next logical step. While AFWL's laser leadership realized that such an experiment would not add much new in the advancement of technology, mainly because the TSL had already demonstrated that the technology worked using the rotoplane target, no laser had ever shot down an aerial target. If the beam could knock a drone out of the sky in true Buck Rogers fashion, then it might win over the Washington "doubters" to gain their support to fund ongoing and future laser programs.[5]

Work officially started on Project DELTA on 13 August 1973. The objective of the experiment was to demonstrate that the integrated TSL and FTT ground system could acquire, track, and destroy an aerial target in a realistic, dynamic

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[4]   *Airborne Laser*, pp. 32-38; Interview with Dyble, 1 Aug 1988; Rpt, David R. Dean, et al., "Field Test Telescope/Air Force Laser Integration Test Results," AFWL-TR-74-225, Sept 1974, pp. 73-94.

[5]   *Airborne Laser*, p. 39; Interview, Duffner with Maj Gen Donald L. Lamberson, USAF, Office of the Assistant Secretary of the Air Force for Acquisition, 12 Jan 1989; Interview, Duffner with Lt Col Danny Boesen, USAF, Retired, 30 Sept 1988; Interview, Duffner with Col Richard V. Feaster, USAF, Retired, 12 Jan 1989.

environment. Weighing 248 pounds and measuring over 12 feet long with a wingspan of 11 feet, a Northrop MQM-33B Radio Controlled Aerial Target (RCAT) drone flew at approximately 200 miles per hour over a 4-mile racetrack course at the Sandia (later Starfire) Optical Range, or SOR. The drone actually followed a course between the SOR site and the Manzano Mountains, which served as a natural backstop for the laser radiation in case the beam missed the drone. Army Air Defense Artillery personnel from Fort Bliss's McGregor Range Camp, New Mexico, flew the highly maneuverable drone by radio-remote control, typically in counterclockwise direction.[6]

An infrared or IR precision tracker, mounted on the FTT, tracked the target by "locking on" to the IR heat source given off by the four-cylinder combustion gasoline engine located in the nose of the drone. The IR signature or image of the drone was displayed on a screen in front of the test operator to monitor. For the initial tests, the laser aimpoint was located on the fuselage below the wing root, a calculated offset from the tracking point. The tracker encountered several problems attributed to signal fades, caused by the drone's turns which blocked the line of sight to the engine track point, and by background noises and sun glints, which on numerous occasions caused the tracking gate on the target to break lock. Eventually, several test runs of the tracker against an F-4 aircraft and the fabrication of an optical acquisition device, consisting of a six-power telescope installed on a hand-directed tracking mount capable of "handing off" the position of the drone to the tracker, made the system more reliable.[7]

There were a total of 14 drone test runs during DELTA. Six gave the operators practice in acquiring and tracking the target. For six other tests, the drone was fitted with a Plexiglas or metal plate to measure beam stability. Data

[6] See note above; Rpt, Col Richard V. Feaster, et al., "Project DELTA," AFWL-TR-74-250, Oct 1974, pp. 3-4, 9-10; Film, AFWL, "Project DELTA," 14 Nov 1973.

[7] *Airborne Laser*, pp. 39-40; Rpt, Col Richard V. Feaster, et al., "Project DELTA," AFWL-TR-74-250, Oct 1974, pp. 10, 13, 21.

collected in these tests helped to make corrections to maintain a separate tracking point (the drone's engine) and laser aimpoint. When the laser hit the aimpoint (first the wing root and then the fuel tank in later tests), the energy created by the beam spilled over into the tracking gate. This caused the 3-to-5-micron IR tracker imager to shift its lock-on from the engine to the more intense IR signal reflected from the laser aimpoint. Because the laser aimpoint was a fixed distance from the tracker spot on target, as the tracking point moved, so did the laser aimpoint move off the most vulnerable spot on the target. Adjustments were made to solve this "gate stealing" phenomenon for the last two drone flights.[8]

The last two, and most dramatic, DELTA tests took place in November 1973. To make the tests as realistic as possible, the target fuel tank selected for the drone resembled that of an F-4 aircraft in combat. The tank was made of 0.06-inch steel, pressurized to 15 psi, and filled with half a gallon (2 liters) of JP-4 jet fuel. During the rehearsal to make one final assessment of the pointer and tracker accuracies, the beam missed the drone and hit a weather tower downrange from SOR. The laser produced a dramatic flash of light as it struck the tower. No damage was done, although the beam left scorch marks on the tower's metal supports. Technicians hurried to make corrections, increasing the distance between the laser aimpoint and track point for the next drone run. Shortly after noon on 13 November, the beam hit the aluminum fuselage aft of the fuel tank. The beam remained on the drone long enough to burn through the skin, causing the drone to lose control and make one last diving left turn before crashing into the desert floor. Inspection of the debris revealed the beam had burned and shorted out the internal electrical control cabling, forcing the drone into a rolling pitch-down maneuver. Although the experiment disabled the drone,

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[8]   *Airborne Laser,* p. 40; Rpt, Col Richard V. Feaster, et al., "Project DELTA," AFWL-TR-74-250, Oct 1974, p. 32; Article, John G. Duffey and Darrell E. Spreen, "Project DELTA," *Journal of Defense Research, Series A: Strategic Warfare—High Energy Lasers,* vol. 4A, No. 1, May 1975, pp. 41-47.

it suffered only minor damage. A recovery parachute was deployed as soon as the drone went out of control to reduce the impact of the drone hitting the ground.[9]

The next day, AFWL's scientists directed the beam squarely on the center of the JP-4 fuel tank located inside the drone fuselage just aft of the engine. Heat created by the beam remained on target for only 1.2 seconds, but that was enough time for the laser to sufficiently raise the temperature of the steel tank to ignite the fuel vapors inside, producing sufficient overpressure to rupture the tank. In a spectacular blaze of fire and smoke, the disabled drone tumbled 200 feet before hitting the ground. Prior to impact, the engine separated from the drone. A parachute deployed to float the engine to earth as a safety precaution; the engine landed approximately 300 meters from the rest of the drone. The bolts holding the tank together severed, and the "main weld seam long the length of the tank blew," turning the tank into an almost flat sheet of metal.[10]

Those who witnessed the historic events of 13 and 14 November 1973 realized Project DELTA was a major milestone, because for the first time a high-energy laser beam shot down a flying target. It clearly demonstrated that all of the functions of an integrated system – acquisition, tracking, and pointing the beam to the aimpoint on the target – worked against an airborne target. In essence, AFWL believed they had solved the basic physics problems of generating a highly focused beam, and processing it with optical surfaces to

[9] *Airborne Laser,* p. 40; Rpt, Col Richard V. Feaster, et al., "Project DELTA," AFWL-TR-74-250, Oct 1974, p. 33; Article, n.a., "DOD Increasing Laser Weapons Development Budget: Airborne Tests Plan," *Aerospace Daily,* 21 March 1975, p. 113.

[10] *Airborne Laser,* p. 40; Interview with Dyble, 1 Aug 1988; Interview, Duffner with Dr. Petras V. Avizonis, AFWL/ARTO, 16 Dec 1988; Interview, Duffner with Col Keith Gilbert, USAF, Retired, 31 Aug 1988; Interview, Duffner with Col Demos T. Kyrazis, USAF, Retired, 20 June 1985; Rpt, Col Richard V. Feaster, et al., "Project DELTA," AFWL-TR-74-250, Oct 1974, pp. 33-34.

direct the beam to its target. Based on this scientific achievement, AFWL scientists were confident they could scale up the power level and propagate the beam in the atmosphere to distances of several kilometers. Success also verified the concept that operational aircraft (simulated by the drone) were extremely vulnerable to lasers. Considering that lasers had only existed for 13 years, DELTA's success took on even more meaning.[11]

Having scored the first shootdown of an aerial target by a laser, Project DELTA clearly established that the Air Force was ahead of the Army and Navy in terms of laser demonstration programs. It wasn't until the summer of 1976 that the Army used an AVCO electric discharge laser to disable a 300 miles per hour, 15-foot-long Beech Aircraft winged drone and helicopter drones at Redstone Arsenal, Alabama. The Navy did not succeed in a similar laser demonstration until March 1978, when it fired a 400-kilowatt deuterium fluoride high-energy chemical laser built by TRW and a precision pointer tracker built by Hughes to shoot down an Army TOW (tube-launched, optically tracked, wire-guided) antitank missile (6-inch diameter) launched near San Juan Capistrano, California. This is not to suggest the Army and Navy shootdowns were not important. Indeed, they were major accomplishments, but it was the Air Force that had struck first. The small AFWL group at the remote SOR site in 1973 had made a valuable technical contribution by reaffirming the Air Force was the leader in the overall high-energy laser program. [12]

DELTA was an important technical accomplishment, but, more importantly, it served as a political rallying point to sustain laser work in general and, more

[11]   *Airborne Laser,* 40-41; Ltr, Col. Allison, Chief, Office for Security Review, Office of Public Affairs, HQ USAF, to AFSC/PAS, "Fact Sheet and Film—DELTA," 29 Aug 1980, with attch: Fact sheet, n.a., "Project DELTA," n.d.

[12]   *Airborne Laser,* pp. 40-41; Interview with Dyble, 1 Aug 1988; Interview with Gilbert, 31 Aug 1988; Article, n.a., "U.S. Nears Laser Weapon Decisions," *Aviation Week & Space Technology,* 4 Aug 1980, pp. 48-54.

particularly, persuade the purse-string holders and the doubters, unfamiliar with the new technology of lasers, of the critical importance of moving forward with the Airborne Laser Laboratory. Armed with the stunning DELTA film that had captured the successful shootdown in Technicolor, AFWL leaders briefed at the Pentagon, Air Force Headquarters, Defense Advanced Research Projects Agency, Scientific Advisory Board, Systems Command, Strategic Air Command, Tactical Air Command, Aerospace Defense Command, and Congress to give them firsthand visual evidence of the damage lasers could do. After watching the film, few could dispute that AFWL had taken the laser to the field and had applied it in a real-world scenario. Moving the integrated laser–acquisition, pointing, and tracking device from the ground onto an airborne platform was the logical next step. With the 1983 shootdown of AIM-9 missiles and BQM-34A drones, the ALL proved that this technology could be successfully operated in the more challenging turbulent atmosphere. A more powerful Chemical Oxygen-Iodine Laser, coupled with a more sophisticated adaptive optics system for use in acquisition, pointing, and tracking, would be found in the Airborne Laser currently being developed–again, the Air Force's next logical step. [13]

[13] *Airborne Laser,* pp. 41-42; Interview, Duffner with Col Edward A. Duff, Air Force Space Technology Center, 13 Sept 1988; Interview with Gilbert, 31 Aug 1988.

High Bypass Turbofans

The development of the high-bypass turbofan engine had the greatest impact on civilian and military aviation since the introduction of the jet (turbine) engine in the 1940s. It enabled fuel-efficient, cost-effective large-bodied aircraft such as the Boeing 747 and Lockheed C-5 transport. High-bypass turbofans employ a large fan as part of the jet engine's first stage. Conventional engines send nearly the same amount of incoming air through the engine as around it. A high-bypass engine's fan can send as much as twelve times as much air around the engine as into it. The bypass air is accelerated by the fan, very similar to the action of a very efficient propeller, which produces additional thrust at the cost of very little fuel consumption. The result is a high-thrust engine that also is very fuel efficient. The downside is that such an engine requires a very large fan, thus obviating its use in tactical aircraft.

The advent of the high-bypass turbofan was the result of the confluence of two factors within the Air Force. In the post-Korean War period, the military underwent a crisis in the way it handled its cargo transportation functions. At that time, the military placed little priority on the airlift function. The Army relied heavily on sealift capabilities and did not view the current generation of aircraft as capable enough to transport its materiel, particularly armor. The Air Force for its part held strategic bombing at the forefront, with tactical aircraft a distant second, and airlift an even more distant third. Congressional concern over the Air Force's outmoded and outdated fleet of propeller-driven cargo planes overrode the DoD's reluctance and culminated in a push for modernization. The jet-powered C-141 *Starlifter* was the first embodiment of this program. Its configuration and versatility were revolutions in military transport. In 1962, the Air Force released its *Operation Forecast* report, which projected and established its development priorities over the coming decade. That report anticipated the need for even

greater heavy-lifting aircraft. The Air Force's Aero Propulsion Lab[1] and its contractor General Electric Aircraft had a hand in shaping the vision for the propulsion system to power such a vehicle. As a result of *Operation Forecast*, the Air Force's Aeronautical Systems Division (ASD) issued requirements for the largest transport aircraft in the world, dubbed the CX-HLS (Cargo Experimental – Heavy Logistics System). Once completed, the program became the C-5 *Galaxy*.[2]

At the same time the Air Force was revising its air mobility function, it both severed and reinvigorated its research in aircraft turbine engines. In October 1957, the Soviet Union launched its *Sputnik* satellite, instigating the space revolution. For the members of the Air Force's Propulsion Lab, this meant the first "migration to space," and the devastation of its turbine engine research to the point where it received no funding for that function in 1959. That drop off coincided with a reorganization of the Air Force lab system such that the responsibility for new operational engines (for specific aircraft) was taken out of the labs and given to ASD. In order to reassert the relevance of his division in the space age and in light of the lab's new operational restrictions, Turbine Engine Division Chief, Ernest C. "Cliff" Simpson, advocated the "gas generator" or "building block" concept of engine research and development. The gas generator, or core, section of an engine consists of the compressor, combustor, and turbine. Since constructing and testing entire engines was both too expensive and now outside the Propulsion Lab's purview, improving components in the smaller and more versatile cores proved an enduring stroke of inspiration.

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[1]   Today's AFRL Propulsion Directorate was the Power Plant Lab from 1939-1957, the Propulsion Lab from 1957-1963, and the Aero Propulsion Lab from 1963-1980s.

[2]   Book, Roger Launius and B.J. Dvorscak, *The C-5 Galaxy History: Crushing Setbacks, Decisive Achievements* (Paducah, KY: Turner Publishing Co., 2001), pp. 10-14; Book, James J. St. Peter, *The History of Aircraft Gas Turbine Engine Development in the United States...A Tradition of Excellence* [hereafter cited as *History of Aircraft*], (Atlanta: American Society of Mechanical Engineers, 1999), pp. 327-328.

The first programs to use the idea were contracts with Pratt & Whitney (P&W) and General Electric for the Lightweight Gas Generator (LWGG). However, the lab had to convince the various engine contractors that this was the way forward, because the idea was radical at the time and its success was not assured or embraced. For contractors, this was a conceptual leap: their component work would not all be for the same "airflow unit." In other words, several years and millions of dollars in contracts would not result in a particular contractor ending up with a singular, superior engine. Despite this reticence, the LWGG program proved very successful in the early 1960s and led directly to the establishment of the follow-on Advanced Turbine Engine Gas Generator (ATEGG) program in 1965. ATEGG is now part of AFRL's Integrated High Performance Turbine Engine Technology (IHPTET) program.[3]

Simpson's gas generator programs joined with the lab's other work in turbofan engines. While dating back to the 1940s, the idea of placing a fan ahead of the compressor was little pursued until the Power Plant Lab's Technical Director Opie Chenoweth strongly advocated the concept. By 1949, the Air Force revised its specifications for the B-52 to include a turbofan for its excellent fuel consumption. Test data from B-52s using later-model engines indicated lower-than-calculated drag on its engine nacelles. Cliff Simpson described this as something of a "eureka" moment when it was realized that nacelle drag was

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[3]   Book, James J. St. Peter, ed., *The Last Great Act of Defiance: The Memoirs of Ernest C. Simpson* [hereafter cited as *The Last Great Act of Defiance*], (WPAFB, OH: Aero Propulsion Laboratory, 1987), pp. 64-65; Book, Aeronautical Systems Center History Office, *Splendid Vision, Unswerving Purpose,* (WPAFB, OH: ASC, 2002), pp. 338-339; Report, Fred W. Oliver, WL/POO, "Old Aero Propulsion Laboratory ADPs," 18 Mar 1980; Report, Marvin A. Stibich, WL/POT, "History of Two Demonstrator Engine Programs," Technical Memorandum APTC-TM-67-17, October 1967; Interview transcript, Thomas J. Sims, with James J. St. Peter, 2 January 1986, in Book, *The Memoirs of Ernest C. Simpson, Aero Propulsion Pioneer: Collected Oral History Interviews Part 1,* James J. St. Peter, ed., AFWAL Special Study, 1 April 1988, p. 267; Interview transcript, Gen Phillipe O. Bouchard, with James J. St. Peter, 8, 15, 22 January 1986, in: *The Memoirs of Ernest C. Simpson: Collected Oral History Interviews Part 1,* p. 332.

not proportional to the airflow as had been previously assumed. That recognition opened the door for engines with larger frontal area, such as ones employing a frontal fan of greater proportions.[4]

In its CX-HLS program, the Air Force provided the need for a high-bypass turbofan engine, while the Propulsion Lab supplied the capability in its gas generators and removal of the theoretical barriers to larger engines. Bringing these elements together required a demonstration proving that the high-bypass idea would actually work. The Propulsion Lab studied the idea and experienced initial skepticism from the aircraft industry concerning its ability to make such an engine work. In 1961, the lab teamed with NASA Ames, the Army, and General Electric in cobbling together a preliminary "poor-man's version" high-bypass engine. The fan was the crucial component, and it was paired with a gas generator developed under the LWGG program. Wind tunnel tests showed the engine had a 12:1 bypass ratio, radically higher than any other engine. General Electric was thoroughly convinced of the concepts' merits and had, by the end of the year, completed rig testing of the various components of a completely functional engine, called the GE-1. Unfortunately, the Propulsion Lab did not have funds to support engine assembly (though they offered much encouragement), but GE adamantly pursued the GE-1 using its own funds. However, it was Lycoming that built and ran the first successful high-bypass engine, its PLF1A-2, which had a 6:1 bypass ratio.[5]

[4] *History of Aircraft*, pp. 173-175; *The Last Great Act of Defiance*, pp. 40, 64-65; Book, Lori S. Tagg, ASC/HO, *Development of the B-52: The Wright Field Story* (WPAFB, OH: ASC/HO, 2004), pp. 48-49; Rpt, Charles R. Hudson, "Appendix 1: Propulsion and Power," in *R&D Contributions to Aviation Progress (RADCAP)*, Vol. II, Mar 1972, pp. 10-11.

[5] *The Last Great Act of Defiance*, p. 65; *History of Aircraft*, pp. 327-328; Book, General Electric, *Seven Decades of Progress: A Heritage of Aircraft Turbine Technology* [hereafter cited as *Seven Decades*], (Fallbrook, CA: Aero Publishers, Inc., 1979), pp. 148-149; Book, Squire Brown, *A Genesis Workshop* (WPAFB, OH: ASC/HO, 2003), p. 41.

The GE-1 engine demonstrator, with its 8:1 bypass ratio and extremely low fuel consumption proved revolutionary in its capabilities. For its part, the Propulsion Lab built a 10:1 bypass ratio model to prove to the reticent aerodynamic community that these engines were feasible. Both the lab and GE discovered that the key to getting a high-bypass fan working was to increase the turbine inlet temperature, which required better turbines. Turbine blade cooling concepts developed under the lab's auspices proved the answer to that problem. Without it, the concept was unworkable. By 1963, GE had a working engine model and the Propulsion Lab was eager to see the GE-1 compete for the CX-HLS (now renamed CXX) engine contract. However, GE felt Air Force leadership weighed against them based on lingering impressions from the past. Cliff Simpson and the lab insisted GE was welcome in the competition and in fact had a considerable lead over its competitors. The proposals were submitted in 1965, which resulted in General Electric winning the contract. Its TF39 high-bypass ratio engine for the C-5 became the company's single largest contract. By that time, other companies including Rolls-Royce and Pratt & Whitney had accepted the concept and were building their own such engines.[6]

The selection of GE for the C-5 engine contract did not end the development of the TF39, nor the lab's involvement with the program. The Aero Propulsion Lab continued to work with General Electric and the engine program office to see the TF39 through its development contract. This proceeded smoothly at first, but suffered major setbacks in early 1967 ahead of its Preliminary Qualification Test. However, analysis and redesigns kept the program going apace despite turbine failures, engine seizures, and foreign object damage – none of which was uncharacteristic for a new engine design. The high bypass turbofan first took to

[6] *History of Aircraft*, pp.328-329; *The Last Great Act of Defiance*, pp. 65-67; Interview transcript, Gerhard Neumann, with James J. St. Peter, 21 April 1987, in Book, *The Memoirs of Ernest C. Simpson, Aero Propulsion Pioneer: Collected Oral History Interviews Part 2*, James J. St. Peter, ed., AFWAL Special Study, 1 April 1988, pp. 647-649, 652-658; *Seven Decades,* pp. 150-152; Book, Gerhard Neumann, *Herman the German* (New York: William Morrow & Co., Inc., 1984), pp. 233-236.

the air on a B-52 test bed on 9 June 1967. In March 1969, the first C-5A with TF39 engines flew, ushering a new ear in large, long-range air transportation. The impact was felt most noticeably in the civilian sector, as Boeing used a Pratt & Whitney high-bypass engine on its new 747 and Douglas used a civilian version of the TF-39 on its DC-10. These aircraft and their engines are credited with revolutionizing mass air transportation, making cross-ocean flights affordable and feasible for the multitudes. Because of the Air Force's role in developing the TF39, it received royalties from GE from each civil version of the engine sold, amounting to some $20 million. Cliff Simpson and GE's Jim Worsham and Don Berkey received the Goddard Award in 1968 for their leadership in developing the high-bypass turbofan.

Hypersonic Aerodynamics and Lifting Reentry

The history of the Air Force's interest in high-speed, high-altitude flight is intimately connected with the AFRL Air Vehicles Directorate (AFRL/VA) and its predecessors, the Aircraft Laboratory (1939-1959) and Flight Dynamics Lab/Directorate (FDL, 1959-1997). That organization had responsibility for the research and development of flight vehicles. Prior to World War II, that purview included little, if any, work in revolutionary new design concepts. Developments in propulsion systems changed that, however, as aircraft speeds increased, especially following the advent of the jet engine and its coming to the United States in 1941. The Aircraft Lab conducted early research into transonic and low supersonic aircraft designs, just as those speeds became feasible. It did early design work on what became the Bell X-1, the first aircraft to break the sound barrier. The earliest definitive work on even faster aircraft, those flown at hypersonic (Mach 5+) speeds, was done in Germany prior to and during World War II. Eugen Sanger and wife Irene Bredt designed on paper what is generally considered the most influential early conceptualization of a realistic aerospace plane (in modern terminology) in the 1930s. For the Air Force engineers who worked in the field in the 1960s, perhaps the most critical figure was Dr. Walter Dornberger. He was in charge of Germany's rocket-powered weapon systems development during the war. As the boss of Wernher von Braun, Dornberger was able to advocate for a winged upper stage of the V-2 rocket. Unlike the Sanger concept, this was actually built and launched on test flights, but the war ended before it was used as a weapon. Dornberger came to the United States under Project Paperclip and ended up at Wright Field for a few years, before joining Bell Aircraft. In both those positions, he was strong proponent of early hypersonic vehicle development.[1]

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[1]   Book, ASC/HO, *Splendid Vision, Unswerving Purpose* [hereafter cited as *Splendid Vision*], (WPAFB, OH: ASC History Office), 2002, p. 323-324; Brfg, Richard P. Hallion, "Hypersonics: Or, Back to the Future – Again and Again" [hereafter cited as "Hypersonics"], 29 Oct 03; Book, Dennis R. Jenkins, *Space Shuttle: The History of Developing the National Space Transportation System* [hereafter cited as *Space Shuttle*],

From the post-War period through the 1950s, high-speed flight research was essentially divided into ballistic missiles and aircraft. The Aircraft Lab directly supported the development of missiles until the creation of Gen Bernard Schriever's Western Development Division in 1954, though the lab continued to provide specific technical expertise when needed. For the labs at Wright Field, the path to hypersonic flight would be through successively faster aircraft. The Air Force took a two-prong approach: exploratory research and development and weapon systems development. The flight research community divided the exploratory R&D effort into three phases. Round One included the first X-planes, like the X-1, which were designed to learn about the aerodynamics and configuration performance in the transonic and supersonic flight regime. That period lasted from the end of World War II until about 1957 and covered the surpassing of Mach 2 by the Douglas D-558-2 Skyrocket and Mach 3 by the Bell X-2. Following those achievements, the winged, ramjet-powered Lockheed X-7 missile broke Mach 4 in 1958. Hypersonic flight also occurred during this interim period, with the Air Force-contracted Alpha Draco research vehicle, a rocket-boosted, slender-cone, hypersonic lifting body. The boost-glide Alpha Draco was more missile than aircraft, but it provided valuable research data for hypersonic heating, aerodynamics, and maneuvering.[2]

The famous X-15 comprised Round Two. This vehicle originated in concept at the National Advisory Committee for Aeronautics (NACA), which became NASA in October 1968. In 1952, NACA's leadership approved a hypersonics research vehicle, while the following year, both the Navy and Air Force began similar programs. This mutual interest stemmed from a lack of suitable test facilities to accurately simulate hypersonic air flow. The only way to obtain that

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2nd ed. (Cape Canaveral, FL: Dennis R. Jenkins), 1997, pp. 1-3, 13; Paper, William C. Walter, "Project Dyna-Soar: The Roots of Shuttle – A Memoir" [hereafter cited as "Dyna-Soar"], International Astronautics Association Paper IAA-92-0193, Sep 92, pp. 1-3.

[2]   *Splendid Vision,* pp. 324-325; "Hypersonics."

data for the envisioned operational vehicles was to create an experimental aircraft to actually venture into that speed regime. The three organizations agreed to collaborate on what became the X-15, with NACA assuming technical lead, while the Air Force held administrative and contractual control at Wright-Patterson AFB's Wright Air Development Center (WADC). The Air Force labs there had a crucial role in choosing a contractor and in developing the vehicle itself as a manned rocketplane/spacecraft. Structures, materials, aerodynamics, and the advanced XLR-99 liquid rocket motor were just some of the technical areas that received input from the labs, but all aspects of the vehicle were overseen by a joint committee composed of NACA, Navy, Air Force, and contractors. Designed to fly faster than Mach 5 and to the edge of space, the X-15 made its first flight in September 1959 and set many records that persisted for decades. Several of its pilots qualified for astronaut wings because of the altitude achieved, with the record being 354,000 feet. Other flights broke Mach 6, topping out at Mach 6.7. The program concluded in 1968 after 199 flights. It was generally considered the most successful and productive flight research program ever undertaken. It paved the way for the space shuttle and other hypersonic vehicles in many fields. It was the source – in some cases, the only source – of invaluable data in structural heating, aerodynamics, structural loadings, guidance and control, propulsion, exo-atmospheric maneuvering, thermal protection, and aerospace medicine.[3]

Concurrently with the Round One developments, the Air Force looked to even more advanced vehicles. The first came unsolicited to the Air Research and Development Command (ARDC), which included the labs, from Walter Dornberger at Bell. Bell proposed building a piloted Bomber-Missile (BoMi), a

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[3] *Space Shuttle*, pp. 7-11; for a complete history of the X-15, see: Paper, Robert S. Houston, et al., "Transitioning from Air to Space: The North American X-15," in *The Hypersonic Revolution: Case Studies in the History of Hypersonic Technology, Volume I, From Max Valier to Project PRIME (1924-1967)* [hereafter cited as *Hypersonic Revolution*], ed. Richard P. Hallion (Washington, DC: Air Force History and Museums Program), 1998, pp. 1-183.

delta-winged glider/rocket atop a rocket booster. Unknown to Bell, the bombing and reconnaissance functions were already under investigation in top-secret ballistic missiles and satellites, setting the stage for later questions over roles and missions. However, the ARDC had a strong an interest in creating a manned, hypersonic flight capability. Bell's work evolved into the Brass Bell program, ostensibly a manned reconnaissance vehicle that affirmed the Air Force's focus on the boost-glide concept, while other contractors came aboard under the aegis of the Rocket Bomber (RoBo) study in 1956. To support RoBo and Brass Bell, the Air Force initiated the Hypersonic Weapon and Research and Development System (HYWARDS). Its purpose was to "provide research data on aerodynamic, structural, human factor, and component problems associated with very high speed flight," and was another collaborative effort among the Air Force, NACA, and their contractors.[4]

In the wake of Sputnik in 1957, all these projects were consolidated into the Dynamic Soaring (Dyna-Soar) program, considered the Round Three vehicle. Aircraft Lab (and future FDL) luminary Bill Lamar was the technical director for this effort to create a manned orbital lifting reentry vehicle. It was a winged spaceplane launched atop a rocket booster and was envisioned variously as a bomber, reconnaissance craft, and pure research vehicle. In 1963, Defense Secretary Robert McNamara cancelled the program for a variety of reasons, including competition from the Air Force version of the Gemini program, mission redundancy with satellites, and technical infeasibility. The Air Force itself provided inadvertent impetus, in that its emerging Manned Orbiting Laboratory (MOL, also based on Gemini) could do many of the space missions and it had started other small-scale programs that replicated much of the research functions of Dyna-Soar. Despite the cancellation, Dyna-Soar provided critical information on hot structures, re-entry aerodynamics, and practical experience for the Air

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[4] *Space Shuttle*, pp. 13-22; "Hypersonics"; "Dyna-Soar," pp. 5-24. For more on Dyna-Soar, see: Article, Clarence J. Geiger, "Strangled Infant: The Boeing X-20A Dyna-Soar," in *The Hypersonics Revolution*, pp. II-ii-xx, 185-377.

Force and its contractors in designing aerospace vehicles. Dyna-Soar is credited as the most direct ancestor of the space shuttle.[5]

With Dyna-Soar on the wane, the Flight Dynamics Lab (FDL) ran more modest experimental efforts, under the aegis of the Spacecraft Technology and Reentry Tests (START) program, to test reusable, maneuverable, re-entry vehicles capable of being flown from earth orbit to a precise landing point on earth. The first of these unmanned test vehicles was the ASV-3 ASSET, or Aerothermodynamic/elastic Structural Systems Environmental Tests. This lifting body was based on earlier FDL designs, particularly those of Alfred Draper, of a winged, flat-bottomed glider and was flown from 1963-65 from Thor rocket boosters. Results from the early X-15 flights helped define ASSET's technical goals, such as hypervelocity configuration evaluation, panel flutter and oscillatory pressure on a trailing edge flap, and investigation of aerodynamic and aerothermodynamic phenomenon in low density flow. ASSET's counterpart program, the SV-5 Precision Recovering Including Maneuvering Reentry (PRIME) was perhaps the most influential of the early studies, as it influenced the shape of future experimental vehicles. Three of these lifting bodies flew from Atlas rockets into space form 1966-1967. In space, each vehicle maneuvered its way back through the atmosphere, demonstrating ablative thermal protection systems, precision reentry guidance, and cross-range maneuvering. Both ASSET and PRIME achieved a great deal technically, without great cost. ASSET and its boosters was accomplished for $41 million, while the more expansive PRIME was just over $70 million, including its rockets. Along with these programs, the Flight Dynamics Lab designed and tested a number of hypersonic glide vehicle designs during the 1960s, notable the FDL-1 through FDL-8 series.[6]

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[5]   *Ibid.*

[6]   Book, James J. St. Peter, *The Flight Dynamics Laboratory: Evolution of an Engineering Miracle* [hereafter cited as *Engineering Miracle*], (WPAFB, OH: Flight Dynamics Laboratory), Oct 88, pp. 135-139; Book, Squire Brown, *A Genesis Workshop* [hereafter cited as *Genesis*], (WPAFB, OH: ASC/HO), 2003, p. 51; *Space Shuttle*, pp. 25,

The research of the 1950s and 1960s accomplished much in terms of proving the feasibility of hypersonic flight. The X-15 and START programs provided very specific technical data that was only able to be accomplished through actual flight tests, while the various vehicle studies and Dyna-Soar laid the early groundwork in terms of programmatics, despite their ultimate lack of results. One aspect remained for investigation: manned atmospheric flight of a lifting body design. The programs of the 1960s essentially settled the Air Force on a wingless lifting body design, that is, one that gets its lift and maneuvering capabilities from its very shape. However, no one knew how one of these shapes would perform in actual flight maneuverings, particularly during precision runway landings. Both NASA and the Air Force separately designed their own lifting body test vehicles in the early to mid-1960s. The Flight Dynamics Lab based its design on the PRIME configuration, which itself was an outgrowth of the years of research done in the lab, and equipped it with a liquid rocket engine. In 1966, the FDL selected Martin Marietta to build the X-24A, which was first flown at Edwards AFB three years later. It reached a maximum speed of Mach 1.6, which was all it needed to explore the low-speed handling characteristics of that type of vehicle, and flew 28 missions through 1971. Results from the X-24A's flights produced immediate results. The FDL had Martin modify one of the X-24A's airframes to match the FDL-7 design, a long, delta-shaped vehicle, then re-dubbed the X-24B. It flew from 1973 to 1975 and proved to be a nearly ideal design. The FDL proposed a follow-on X-24C, capable of hypersonic flight, in concert with NASA, but it was cancelled by NASA after several years of study. The X-24C later served a useful purpose as the subject of the first full vehicle analyzed using computational fluid dynamics, completed by the FDL in 1984.[7]

28-31; For complete histories of ASSET and PRIME, see: Articles, Richard P. Hallion, "ASSET: Pioneer of Lifting Reentry," and John L. Vitelli and Richard P. Hallion, "Project PRIME: Hypersonic Reentry from Space," both in *The Hypersonic Revolution.*

[7] *Space Shuttle*, pp. 36-41; *Genesis*, pp. 51-52; "Hypersonics"; Article, Richard P. Hallion and John L. Vitelli, "The Piloted Lifting Body Demonstrators: Supersonic Predecessors to Hypersonic Lifting Reentry," in *The Hypersonic Revolution: Case Studies in the History of Hypersonic Technology, Volume II, From Scramjet to the*

The Air Force's extensive working in hypersonic aerodynamics and lifting reentry left a lasting legacy: the space shuttle. The research done at the Flight Dynamics Lab influenced that vehicle in many ways. ASSET contributed knowledge of thermal protection and reentry heating for a winged vehicle. PRIME demonstrated maneuvering reentry. The X-24 series provided the critical data necessary for landing the shuttle and it enabled NASA to leave the shuttle unpowered during atmospheric flight. Without those tests, NASA had considered equipping the shuttle with jet engines, at great weight and cost penalties. The lab's contributions to the shuttle were not limited to the flight demonstrations. The basic science and technology behind their development, as well as the actual test equipment, was likewise applied by NASA to the shuttle design. Once flying, the shuttle itself provided the most extensive database on hypersonic flight, which the Air Force was able to take advantage of.[8]

The early success of the shuttle and the earlier hypersonics programs set the stage for the National Aerospace Plane (NASP) program of the 1980s. That multi-agency program renewed interest in hypersonic glide vehicles. Its massive effort provided a great deal of funding for the Flight Dynamics Lab and made possible the modernization of its hypersonics-related test facilities. Unfortunately, NASP literally went the way of the Dyna-Soar, being de-scoped and ultimately cancelled in the early 1990s. The Air Force did not put all its eggs in NASP's basket however. Concurrent with the early phase of NASP, the Flight Dynamics Lab ran the Boost Glide Vehicle (BGV) program. As the name suggests, it drew on the heritage of the lab's programs in that field since the 1950s. This effort was to build a demonstrator model of a suborbital, unmanned hypersonic glider for use as a weapon. It bore close resemblance to the later

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National Aero-Space Plane (1964-1986), ed. Richard P. Hallion (Washington, DC: Air Force History and Museums Program), 1998, pp. 893-945.

[8]   *Engineering Miracle*, pp. 130-139; "Hypersonics."

concepts, but on a smaller scale. The 1984-1986 period saw various studies of its feasibility. Given that much of the technology had been proven in earlier programs, the BGV program received initial support, but failed to come to fruition,. However, the concept persists in the current Air Force Research Laboratory's Air Vehicles directorate (AFRL/VA). A boost glide vehicle is one option for meeting the Air Force's missions of Prompt Global Strike and Long Range Strike.[9]

Hypersonic flight research has an accurate reputation for coming in boom-or-bust cycles. Part of this stems from the inseparable politics associated with any large-scale technological system. Perceived needs and available resources change with a frequency incommensurate with expensive, long-term development programs. Hypersonics is particularly susceptible to these vacillations because it has been and remains among the most complex, difficult, and ambitious of technological enterprises. Despite the fact that practical, air-breathing hypersonic flight has not yet been achieved, it is undeniable that significant progress has been made over the past decades. The predecessors of the Air Vehicles Directorate were second perhaps only to NASA in terms of its overall contributions to that field of research. It has led or been a partner in every major hypersonics program since the 1950s and has been a party to every major advancement in that time. When routine hypersonic flight becomes practical, that achievement will owe much to the legacy of the Air Force laboratories.[10]

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[9]   For a history of NASP, see: Book, Larry Schweikart, *The Hypersonic Revolution: Case Studies in the History of Hypersonic Technology, Volume III, The Quest for the Orbital Jet: The National Aero-Space Plane Program (1983-1995)*, (Washington, DC: Air Force History and Museums Program), 1998; History, Dr. James F. Aldridge, ASC/HO, "History of the Aeronautical Systcms Division January – December 1986 Part II: The Air Force Wright Aeronautical Laboratories, January 1984- December 1986," July 1987, vol. I, pp. 161-164; Website, AFRL/VA, "Air Vehicles Homepage," available on the internet: http://www.va.afrl.af.mil/, as of 1 Dec 05.

[10]   *Engineering Miracle*, p. 137; "Hypersonics."

Integrated Avionics

The integration of avionics systems and subsystems on modern military aircraft arose from the proliferation of aviation electronics (=avionics) following World War II. The Air Force's principal organization for both developing avionics components, systems, and their integration has been the Air Force Research Laboratory's Sensors Directorate (AFRL/SN) and its predecessor organizations, especially the Air Force Avionics Laboratory (AFAL), Wright-Patterson AFB, Ohio.

The Air Force's laboratories have been involved in developing electrical and electronic instrumentation for aircraft since World War I.[1] In the 1920s this work consisted primarily of designing, testing and installing radio kits, dials, gauges, and lighting.[2] This activity became more complex in the 1930s and especially during World War II, particularly with the introduction of airborne radar sets and antennas. Early electronic equipment, such as radios and radars, incorporated bulky and fragile vacuum tubes and sets that added substantially to the overall weight of aircraft. Electrical and electronic equipment, moreover, was developed and acquired independently of the rest of the air vehicle and was provided as government furnished equipment (GFE) to the prime contractor. This mode of operating continued into the postwar period and throughout the 1950s and

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[1]   At McCook and Wright fields the principal laboratories that developed electrical and electronics equipment and components were the Engineering and Materiel Division's Equipment Laboratory and the Signal Corps' Aircraft Radio Laboratory. In World War II, the Aircraft Radio Laboratory was merged into several new laboratories, including the Radar Laboratory and the Communication and Navigation Laboratory. See Study, Dr. James F. Aldridge, ASC/HO, "An Historical Overview of the Mission and Organization of the Wright Laboratory, 1917-1993" [hereafter cited as "Mission and Organization"], Nov 1994, p. 11.

[2]   See Air Service and Air Corps *Information Circulars*, currently shelved in the AFRL Technical Library's Bldg 57 annex. The *Circulars* represent about 10 percent of the technical reports generated by McCook and Wright fields and cover all aspects of airplane development for the years 1920-1940.

1960s; consequently, development and installation of electronic equipment in Air Force aircraft continued to be done as "standalone threads of functionality with little digital computer processing capability,"[3] also known as "black boxes."

It took some time for the revolution in electronics inaugurated by the invention of the solid state transistor in 1948 and of the integrated circuit (IC) a decade later to gain momentum. However, dramatic advances in solid state microelectronics during the 1960s and 1970s made possible—even imperative—the integration of avionics in Air Force aircraft. This integration was also made possible by the revolution in the organization and operation of the Air Force's laboratories in the late 1950s and early 1960s, particularly the creation of AFAL by consolidating a number of smaller electronics and sensors laboratories at Wright Field, from 1959 to 1963.[4]

In the early 1970s, the Avionics Laboratory took advantage of the growing maturity of solid state microelectronics, particularly computers, to lay out a long-term program for integrating all on-board electronics into a rational and consistent avionics architecture.

The first program under the new approach was the Digital Avionics Information System (DAIS) that ran from 1972 through 1981. DAIS demonstrated technologies in four areas: (1) digital multiplex buses, (2) higher order language (HOL) operational flight program design, (3) standard computer

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[3]   Report, Dr. James F. Aldridge, ed., ASC/HO, "USAF Research and Development: The Legacy of the Wright Laboratory Science and Engineering Community, 1917-1997" (draft), [hereafter cited as "USAF R&D"], 1996, p. 97.

[4]   This consolidation brought together the Reconnaissance Laboratory (radar), Navigation and Guidance Laboratory, Communications Laboratory, and the Electronic Technology Laboratory, all stand-alone units under the Wright Air Development Center (1951-1959). See "Mission and Organization," p. 15.

instruction set architecture (ISA) for multiple federated processors, and (4) integrated multi-function cockpit controls and displays based on multi-purpose cathode ray tubes (CRTs) and digital, programmable display generators.[5] The DAIS program resulted in the development and transition to operational systems of MIL-STD-1553B multiplex buses and a standardized remote terminal interconnect to subsystems; MIL-STD-1750A 16-bit ISA with support software standardization; MIL-STD-1589B JOVIAL[6] HOL standardization, programming environment, and DAIS operating system; and the concept and format of integrated controls and displays. Among the military aircraft benefiting from DAIS were the F-15, F-16, B-52, B-1B, F-117, and the C-17. [7]

The Avionics Laboratory followed up its successes with DAIS by participating in "third generation" avionics architecture development efforts described collectively as Pave Pillar.[8] Among the program efforts falling under Pave Pillar were the Integrated Communication Navigation Identification Avionics (ICNIA) program,[9] the Integrated Electronic Warfare System (INEWS) program,[10] and the

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[5]   "USAF R&D," p. 97.

[6]   JOVIAL = Jule's Own Version of International Algebraic Languages.

[7]   "USAF R&D," p. 97.

[8]   Annual History, Dr. James F. Aldridge, ASC/HO, "History of the Aeronautical Systems Division, CY 1986, Part II: The Air Force Wright Aeronautical Laboratories, CY 1984-1986" [hereafter cited as "AFWAL"], vol. 1, pp. 100-102; Technical memorandum, Robert L. Harris, ed., "A Scrapbook of Published Papers Related to Integrated Communications Navigation Identification Avionics (ICNIA)," AFWAL-TM-83-21-AAAI, June 1983; Technical memorandum, Robert L. Harris, ed., "A Scrapbook of Papers Related to Integrated Communication Navigation Identification Avionics (ICNIA)," AFWAL-TM-87-AAAI, April 1987; Chronology, n.a., "ICNIA Chronology," n.d. [1986]; Background paper, n.a., "Integrated Communication Navigation Identification Avionics (ICNIA)," 31 Oct 86.

[9]   "AFWAL," pp. 97-99.

[10]   *Ibid*, pp. 103-104.

Air-to-Air Attack Management (AAAM)[11] and Pilot Associate programs. Pave Pillar furthered the development of integrated systems and exploited such technology advances as Very High Speed Integrated Circuits (VHSIC),[12] fiber optic high speed data buses, and the DOD-sponsored ADA computer language. The Pave Pillar program was active from 1983 to 1987. Its technologies have particularly benefited the F-22[13] and Commanche development programs. Pave Pillar was also the first program to attempt to develop tri-service common modular avionics among the Air Force, Army, and Navy under the Joint Integrated Avionics Working Group (JIAWG).[14]

Pave Pillar was followed in 1990 with the Progressive Avionics Concept Evaluation (PAVE PACE) program. PAVE PACE was developed for multi-role, multi-service platforms emphasizing affordability and cost effective service lifetimes. PAVE PACE technology drivers included microwave/millimeter integrated circuits (MIMICs), super computing, optical radio frequency (RF) and digital networks, and maintenance-free avionics [15] Technologies and approaches developed under PAVE PACE contributed to the F-35 Joint Strike Fighter avionics suite.[16]

The end of the Cold War confronted the Air Force avionics community with a number of potential problems and opportunities. With fewer new aircraft systems being acquired that had been designed from the start with integrated

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[11]   *Ibid,* pp. 104-106.

[12]   *Ibid,* pp. 94-96.

[13]   Intvw, John Ostgaard, AFRL/SNAR, with Dr. James F. Aldridge, AFRL/HO, 21 Nov 2005.

[14]   "USAF R&D," p. 98.

[15]   *Ibid.*

[16]   Intvw, Ostgaard with Aldridge.

avionics suites (like the F-22 and F-35), increasing reliance was placed on older, so-called "legacy" systems. Legacy systems, by and large, incorporated older "black box" avionics suites that had been available at the time of their manufacture and incorporated in subsequent upgrades and repairs. In order to upgrade these systems in the future to take advantage of the advances in integrated architectures developed in the 1970s and 1980s, the Air Force, in the mid 1990s developed an "open architectures" approach. Open architectures offered the opportunity to incorporate the latest commercial-off-the-shelf (COTS) advances in electronics within an overall integrated framework that permitted incremental upgrades, as technological advances and budgetary constraints dictated.[17]

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[17]   Paper, John Ostgaard, Juan Carbonell, and Stephen Benning, "Aging Avionics—A Science & Technology Challenge or Acquisition Challenge?", n.d., passim; Paper, Glen T. Logan, "Department of Defense Perspective on Open Systems Architecture," AGARD Conference Proceedings 581, AGARD-CP-581, pp. 4-1 through 4-8; Paper, C. H. Krueger and R. Venner, "When Do Advanced Avionics Architectures Make Sense for Upgrading Aging Aircraft?", AGARD Conference Proceedings 581, AGARD-CP-581, pp. 7-1 through 7-10; Paper, Juan Carbonell and John Ostgaard, "Impact of COTS on Military Avionics Architectures," AGARD Conference Proceedings 581, AGARD-CP-581, pp. 29-1 through 29-5; History, ASC/HO, "History of the Aeronautical Systems Center, FY 2000," vol. 1, pp. 47-52.

Integrated Computer Aided Manufacturing

On 21-22 June and 18-20 July 1972, two technical workshops were held (in Dayton and Cincinnati) to establish the direction of an Air Force program aimed at unifying the many separate approaches of industry and academia to computerize the machine-tool industry. Air Force officials hoped that the program would help revitalize the U.S. industrial base and improve the competitive position of the United States. Participants in the workshops included members of the aircraft, turbine engine, and missile prime contractor and subcontractor community; machine-tool builders and controller producers; software producers; and academics. Firms participating in the workshops included Metcut Research Associates Incorporated, Universal Technology Corporation, General Dynamics Corporation, the Boeing Company, Lockheed Aircraft Corporation, McDonnell Douglas Corporation, North American Rockwell-Rocketdyne, General Electric Company, and TRW Incorporated. Gail E. Eichelman and William A. Harris represented the Air Force Materials Laboratory (AFML) Manufacturing Technology (ManTech) Division. The industry leader of the workshops was Dr. Michael Field, president of Metcut Research Associates.[1]

Field summarized the conclusions of the Cincinnati meeting as follows. (1) Increasing productivity and reduction of costs in the modern manufacturing environment will require increasing application of computer-aided manufacturing (CAM) -- a powerful, new management engineering tool that offers the potential of optimizing the entire manufacturing process through a systems approach to cost reduction. (2) ManTech should assume the role of CAM leadership because the Air Force's CAM requirements are unique and critical. (3) The precise meaning of CAM needs to be clearly identified. (4) The CAM program needs to

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[1]   Book, Universal Technology Corporation, *History of the Air Force Materials Laboratory, Volume II, Part II: Landmark Technology Programs 1960 to 1990* [hereafter cited as *Landmark Technology*], Report No. ASC/PA#ASC-00-0912, March 2000, p. 117.

accompany all aspects (design, manufacturing, quality control, material handling, and all managerial functions) of planning and producing a manufactured part. (5) An optimal manufacturing system is one that meets a specified production rate and quality requirement at minimum cost. (6) CAM development efforts should be directed toward producing standard separable and isolatable "packaged" hardware/software modules of each CAM element. (7) A "total systems" approach to the application of CAM concepts and techniques is essential. (This would include as a prerequisite a flexible interfacing system built around a common management information system structure that would allow users to assemble selectively a CAM system tailored to their particular needs.) (8) Finally, because the introduction of a large-scale CAM system into a company would likely entail major financial expenditures, top management must initiate or completely support the implementation of such a system to make it successful.[2]

A major recommendation of the participants of the workshops was that ManTech should set up and manage an Air Force Computer Aided Manufacturing (AFCAM) program. ManTech's Metals Branch thus contracted the Boeing Company and subcontractor Softech to develop a master plan for an AFCAM program. The companies, in a five-volume report, proposed formalizing a common architectural language to deal with the great diversity of technical disciplines, end products, and needs of prime and subcontractor organizations. They also called for the development of a glossary of terms, a cell concept of manufacture, a management concept, and modules for CAM. Computer-aided-design/computer-aided-manufacturing (CAD/CAM) consultant Dr. Joseph Harrington discussed the Boeing/Softech concepts with 19 companies selected as representatives of the aerospace community. The "master plan" report was

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[2]   *Ibid*, pp. 118-119.

then formally presented to executives of government, industry, and academic institutions at a meeting in Chicago, Illinois, in July 1974.[3]

Following a review of the Boeing/Softech "master plan" document and user-community comments upon it, ManTech chief James Mattice asked the Air Force Systems Command (AFSC) to review the AFCAM documentation and recommendations. AFSC appointed Col. John Neese to lead a team of specialists who conducted a yearlong in-depth review of the AFCAM program and its potential effect on the industrial base. Their review, together with an intense program advocacy by ManTech deputy chief, Dr. Cyril Pierce, led to an Integrated Computer Aided Manufacturing (ICAM) program that the division presented to industry on 13 April 1976. This program proposed nothing less than the use of computers to control every stage of production to increase productivity and reduce manufacturing costs. Describing their program as "ambitious and far-reaching" and potentially "revolutionary," the planners believed that if CAM could become a fully integrated process, it would "allow production to be performed in a way that today is only barely comprehensible managerially and technically." They envisioned two goals in particular: (1) a planning ability allowing engineers not only to design a part optimally, but also simultaneously to subject the part to a performance evaluation and quickly plan its most economical fabrication within the constraints of schedule, availability of raw materials, and variability of materials and processes; and (2) an ability to hold design and processing information in standard data formats and deliver it "on time" in any appropriate medium for an executive's staff to perform "what if" simulation assessment ranging from risk analysis to plant layout.[4]

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[3]   *Ibid,* p. 120; Tech report, Air Force Materials Laboratory, "Air Force Computer-Aided Manufacturing (AFCAM) Master Plan," Report No. AFML-TR-74-104, July 1974.

[4]   *Landmark Technology,* p. 120; Report, Universal Technology Corporation, "History of the Air Force Materials Laboratory, Volume II, Part IIIA: People and Events 1965 to 1977" [hereafter cited as "People and Events"], September 2003, p. 148.

Considering the ICAM program to be ManTech's principal response to Deputy Secretary of Defense W. P. Clement's request for major new manufacturing initiatives, division officials applied for and received, in September 1976, approval for a $75-million appropriation to conduct a USAF Integrated Computer Aided Manufacturing (ICAM) program from FY 1977 to FY 1982. The ICAM program management directive, issued on 18 January 1977, listed five objectives: (1) reduce defense system costs by developing and applying CAM technology for the fabrication of defense material; (2) establish a model for the integrated application of computer technology to all phases of production and manufacturing; (3) improve the long-term competence, efficiency, and responsiveness of U.S. aerospace and related industries to defense needs; (4) provide a mechanism for ICAM technology to link with U.S. industry; and (5) validate and demonstrate the cost-savings benefits and flexibility of ICAM for representative elements of Air Force systems production.[5]

The ManTech division funded various Center Demonstration Projects to apply the tools developed by ICAM and other governmental, institutional, and industrial offices. A project with the Boeing Company to develop an integrated sheet metal center concentrated on integrating business systems and closing the loop from the master schedule down through shop floor control. General Dynamics Corporation, working with ManTech's Metals Branch, conducted an advanced machining system program that included business integration and pursued technical systems by addressing generation and delivery of machine control instructions. LTV's Vought Aero Products Division project to develop a conceptual design for computer-integrated manufacturing was a component for advocacy of the "factory of the future."[6]

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[5] *Landmark Technology,* p. 121; "People and Events," pp. 165-166.

[6] *Landmark Technology,* p. 122.

Limited funding did not permit completion of the ICAM effort as initially envisioned. Nevertheless, the AFCAM and ICAM programs were timely catalysts for modernization and revitalization of the aerospace manufacturing base. The development of CAD/CAM was one of ten technologies that the National Academy considered as "outstanding achievements" made during the first 25 years (1964-1989) of the existence of the academy.[7]

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[7]   *Landmark Technology*, p. 123.

Jet Fuels

The history of jet fuels began humbly when the Wright brothers poured several cans of standard motor gasoline, obtained from a boatyard, into the specially-built engine on their first Flyer. Later estimates gave this fuel an octane rating of 38. The growth of the automobile and aviation prompted some improvements in refining gasoline, but the United States discovered in World War I that its fuels were not up to the standards of advanced, high-performance European aircraft engines. The wide variety of fuels, based on the natural variation in petroleum and a lack of standardization further complicated this matter. The key early developments that led to high-performance fuels used in military aviation came from private industry devoted to motor vehicle fuels. A Briton working for the Shell Company developed the first understanding of gasoline knock properties, while Thomas Midgley's experiments with anti-knock compounds at the behest of Charles Kettering resulted in the use of tetraethyl lead to alleviate knock. Prior to the Second World War, military aviation used only a miniscule amount of overall refined petroleum products, thus its needs did not prompt significant independent commercial innovation.[1]

Following World War I, the Army Air Service's new laboratories at McCook Field, Dayton, Ohio, began sporadically investigating aviation fuels under its Power Plant Section (now AFRL/PR). Its early work in resolving engine knock was a direct result of the poor quality fuel it received for its engine experiments,

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[1]   Paper, Tim Edwards, "Liquid Fuels and Propellants for Aerospace Propulsion: 1903-2003" [hereafter cited as "Liquid Fuels"], *Journal of Propulsion and Power*, vol. 19, no. 6 (Nov-Dec 03), pp. 1089-1090; Paper, Alexander Ogston, "A Short History of Aviation Gasoline Development, 1903-1980" [hereafter cited as "Aviation Gasoline"], in Book, *History of Aircraft Lubricants,* ed. by Lyle Cummins (Warrendale, PA: Society of Automotive Engineers, 1997), pp. 1-14; Book, S. D. Heron, *History of the Aircraft Piston Engine* (Detroit: Ethyl Corporation, 1961), pp. 75-83; Paper, S.D. Heron, "Development of Aviation Fuels" [hereafter cited as "Aviation Fuels"], in Book, Robert Schlaifer and S. D. Heron, *Development of Aircraft Engines and Fuels* (Boston: Harvard University, 1950), pp. 549-550, 581-599.

and was based heavily on the results of Midgley's work at the nearby Dayton Engineering Laboratory Company (Delco). In 1928, the Power Plant Branch's (now relocated at Wright Field) director implemented the military's first systematic investigation of aviation fuels, which was both influenced by and confirmed the earlier work done in the private sector. The ensuing program enabled the Army Air Corps to address the specific problems associated with increasingly higher performing aero engines and even pushed fuel companies to adopt the standards and innovations developed in the Wright Field laboratories. Critical early lab discoveries included the effects of engine cylinder temperature on fuel performance, first military aviation fuel specifications, the first use of the octane number as an expression of anti-knock in aviation fuel, the resolution of many technical difficulties associated with the use of leaded fuels in aircraft engines, and the formulation of the standard 100-octane fuel used in World War II. Samuel D. Heron and Frank Klein led the Power Plant Branch's fuels research during this pre-war period. Research into aviation gasoline produced up to 115 octane fuels by 1944. The following year, production reached its all time peak, over five times that produced at war's outset. The cessation of hostilities resulted in a dramatic decline in production, which never fully recovered in part because of the replacement of piston engines with turbine engines.[2]

The jet engine emerged in laboratory in the late 1930s, went to flight test in 1939 in Germany and 1941 in Britain, and was in limited operation by 1944. Both inventors of the jet engine, Frank Whittle and Hans von Ohain, powered their first prototype engines with fuels determined by expediency. In Whittle's case, aviation gasoline was in short supply due to the onset of World War II. He briefly

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[2] "Aviation Fuels," pp. 582-599; "Aviation Gasoline," pp. 8-9, 12-13; "Liquid Fuels," 1091; Tech rpt, Albert Misenko, "Aero Propulsion and Power Directorate: The McCook Field Years (1917-1927)," AFRL-PR-WP-TR-1998-2080, Feb 95, p. 109; Rpt, Charles R. Hudson, "Appendix 1: Propulsion and Power" [hereafter cited as "Propulsion and Power"], in *R&D Contributions to Aviation Progress (RADCAP)*, Vol. II, Mar 1972, pp. 4-5.

considered diesel fuel, but it had a low freezing point that was incompatible with high-altitude flight, so he turned to kerosene, which was then widely used to light lamps. Von Ohain experienced many initial problems with his combustors when using aviation gas, and instead powered his first experimental turbojet with hydrogen because it was easier to burn. His successful redesigns and the impracticality of liquid hydrogen as an aircraft fuel led his switch back to gasoline. It was widely believed that one advantage of turbines engines was its ability to "run on any fuel from whiskey to peanut butter." While this was technically possible, fuels typically ranged from low-octane gasoline to furnace oil, to the most prevalent kerosene. The first American jet engines, built by General Electric and overseen by the Power Plant Laboratory, copied Whittle's design, including its use of kerosene.[3]

Serious development effort on jet propulsion during the late 1940s proved that proper fuels were as critical for turbine engines as they were for piston engines, though for different reasons. For the latter, superior fuels were key to improving performance in terms of horsepower. The high-octane fuels are credited with achieving nearly half the 400 percent increase in power between equivalent sized engines from World War I and World War II. The anti-knock properties of those fuels enabled the engine to extract every bit of energy out of its fuel. In the case of turbine engines, designers had to balance the fuel's energy content to combat excessive fuel consumption, freeze point, volatility/vapor pressure, and availability/cost.[4]

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[3]   "Liquid Fuels," p. 1091; Tech rpt, Charles R. Martel, "Military Jet Fuels, 1944-1987" [hereafter cited as "Military Jet Fuels"], AFWAL-TR-87-2062, Nov 87, pp. 1-2; Book, Leslie E. Neville and Nathaniel F. Silsbee, *Jet Propulsion Progress* [hereafter cited as *Jet Propulsion*], (New York: McGraw Hill, 1948), p. 129, 183-184.

[4]   "Aviation Fuels," pp. 558-559; *Jet Propulsion*, pp. 183-184; "Liquid Fuels," pp. 1091-1092.

The first American jet fuel specification came in 1944 from the Power Plant Lab[5] as Jet Propellant 1 (JP-1), which was simply aircraft-grade kerosene, mainly for meeting low freezing point and high flash point requirements. Those restrictions limited the availability of JP-1, as only 3 percent of crude oil could be refined to that level. Almost immediately, the Army Air Force began looking for a replacement fuel. The first "wide-cut" distillate fuel appeared in 1945 as JP-2, but it proved unsatisfactory because of its viscosity and flammability. It was limited only to experimental lab use. Still in need of a low-cost fuel to meet the performance and fuel consumption characteristics of operational jet engines, the Power Plant Lab began its search for a fuel of "maximum availability with a minimum of quality requirements." The resulting JP-3 specification in 1947 proved satisfactory in tests in Alaska, particularly its low temperature operability and availability. As JP-3 was a "wide-cut" fuel that included both naphtha (gasoline) and kerosene, it could be refined from approximately 60 percent of crude oil (20 times more than JP-1) and became the standard Air Force jet fuel during the late 1940s. However, further experience with this fuel demonstrated problems with boil-off, vapor lock, and an incompatibility with certain synthetic rubber components.[6]

The drawbacks of JP-3 led the lab to continue its search for a more suitable jet fuel. By 1951, it had completed its evaluation of the next generation fuel and it issued the specification for JP-4 in May. By January 1952, JP-4 became the

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[5]   Note that the histories of jet fuels do not differentiate between the contributions of government and contractor employees. The labs certainly conducted many experiments to define the qualities and effects of fuels provided by industry, which also developed production methods. Thus the references to "the lab" here are inclusive of in-house and contracted research.

[6]   "Liquid Fuels," p. 1091; "Propulsion and Power," p. 13; "Military Jet Fuels," p. 2; Tech rpt, G.T. Beery, et al., "Assessment of JP-8 as a Replacement Fuel for the Air Force Standard Jet Fuel JP-4, Part I. Assessment of JP-8/JP-4 Fuel in Noncombat Environment" [hereafter cited as "Assessment of JP-8"], AFAPL-TR-74-71, Jun 75, p. 5; Rpt, Power Plant Laboratory, "Technical Accomplishments - Power Plant Laboratory, Fiscal Years 1946-1951" [hereafter cited as "Technical Accomplishments"], 3 Sep 51, pp. 110, 112.

standard throughout the Air Force. JP-4 was very similar to its predecessor, but offered a lower vapor pressure. This increase in operability came at the expense of somewhat more limited availability, but not enough so as to keep it from being used by the Air Force for the next four decades.[7]

The long-term success of JP-4 did not end the Air Force labs' investigations of jet fuels. Combat experience in Vietnam demonstrated a critical characteristic of this fuel: a low flashpoint that rendered it highly susceptible to burning when hit by small arms fire. Minor hits to fuel tanks resulted in loss of crew and aircraft, so the Aero Propulsion Lab responded with a deliberate effort to create a lower volatility fuel. The Navy's JP-5 low volatility fuel was difficult to produce and was not available in the quantities demanded by the rest of the DoD. In response to this need, the Lab proposed a variation of the commercial kerosene-based Jet A-1 fuel, supplemented with icing and corrosion inhibitors. In 1968, this mix was chosen for further testing, primarily because of its high flash point and its wide availability (due to its derivation from Jet A-1).[8]

After nearly a decade of development, detailed study, and testing, the Aero Propulsion lab issued the first specification for JP-8 in 1977, and the Air Force began the widespread adoption of the fuel. However, it took nearly twenty years (in 1995) before the Air Force had completely switched to JP-8. Now it consumes about half of the DoD's 5 billion gallons of JP-8 per year. The Propulsion Directorate has continued to study and refine the fuel for better properties, including the JP-8+100 high temperature fuel recently adopted.[9]

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[7] Annual history, Air Materiel Command, "History of Wright Air Development Center," Vol. I – Text, 1 July – 31 December 1951, pp. 223-227; "Military Jet Fuels," pp. 3-4; "Liquid Fuels," pp. 1091-1092; "Propulsion and Power," p. 13; "Assessment of JP-8," p. 5.

[8] "Assessment of JP-8," pp. 1-4, 7-8; "Military Jet Fuels," pp. 7-8.

[9] "Assessment of JP-8," pp. 1-4, 7-8; "Military Jet Fuels," pp. 7-8; History, AFRL/HO, "History of the Air Force Research Laboratory, 1 October 2000-30

It has also explored advanced fuels for aircraft applications outside the mainstays of the fleet. An early example of this work was the creation of the standard for the Navy's universal jet fuel, JP-5. The Navy's use of carrier aircraft necessitated a lower volatility fuel (higher flash point) for safety purposes, while their more limited consumption of fuel meant that a less available fuel could be considered. In fact, the volatility and freezing point restrictions severely limited the availability of JP-5 to the point where the Navy used JP-4 for its land-based operations. The Aero Propulsion Lab developed JP-5, which was adopted in 1952, is still used today, and was even the preferred fuel for the presidential aircraft.[10]

With the proliferation of specialized aircraft that flew outside the normal envelope, unique fuels were needed to power their particular engines or simply to remain viable under rarefied conditions. In 1956, the advent of the U-2 spy plane required a fuel with a lower freezing point to operate at very high altitudes. The Power Plant Laboratory responded with the in-house development of JPTS (Jet Propellant Thermally Stable), still in use today. Its expense has led current efforts to find a replacement based on JP-8 and special additives to make it more affordable and deployable. Similar efforts were done for high-Mach aircraft like the XB-70 bomber and the SR-71 (and its derivatives). These Mach 3+ aircraft required a fuel capable of absorbing more heat, so PR responded with JP-6, also in 1956, for the XB-70 and JP-7 for the SR-71 in 1959 (but kept secret until 1970). As with low-temperature fuels, PR is currently working on variations of JP-8 to enhance its high-temperature properties.[11]

September 2001" [hereafter cited as "AFRL History FY2001"] Vol. I, Apr 02, pp. 438-441.

[10] "Military Jet Fuels," p. 4; "Assessment of JP-8," pp. 5-6; "Liquid Fuels," pp. 1091-1092.

[11] "Military Jet Fuels," pp. 5-6, 12-13; "AFRL History FY 2001," pp. 439-441; Book draft, Albert E. Misenko and Gary D. Streby, *Seventy-Five Year History of the Air Force Aero Propulsion and Power Directorate*, Oct 94, pp. 150-153.

The specialty fuels work in PR extended to weapons as well. The lab was responsible for the development of JP-9, the first cruise missile fuel that offered 20% more range with the same volume of fuel. PR subsequently developed the much lower cost JP-10 in 1979, which has since been adopted as the standard fuel for all DoD cruise missiles. The lab's decades of work in ramjet and rocket engines prompted it to devise special fuels for those applications, as well. The rocket fuel work extended back into the 1940s, when the lab experimented with variations of kerosene and was reportedly the first to try liquid hydrogen as a rocket fuel. The Aero Propulsion Lab's fuels for ramjets became the standard for the Air Force, though that type of engine saw only limited service.[12]

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[12] Book, John L. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945-1959* (Washington: GPO, 1977), pp. 12-14; "Technical Accomplishments," pp. 109-112; "Liquid Fuels," p. 1095; "Military Jet Fuels," pp. 8-12.

Joint Surveillance Target Attack Radar System (JSTARS)

Surveillance of terrain to attack hostile forces is as old as warfare itself. It was among the earliest uses to which aircraft (both lighter-than-air and heavier-than-air) were put. Indeed, the chance sighting of the German line of march by British and French observation planes may well have won for the Allies the First Battle of the Marne—and set the stage for German defeat in World War I.[1] Going airborne to locate specific tactical targets is even older, dating at least to the activities of U.S. Army Signal Corps balloons in the American Civil War. Following World War I, the Signal Corps' Aircraft Radio Laboratory at McCook and then Wright Field, near Dayton, Ohio, introduced the use of electronics in aerial targeting and continued this research into World War II before the laboratory was reorganized into several specialized labs. In 1963, these labs were, in turn, reunited to form the Air Force Avionics Laboratory (AFAL), the principal precursor of the Air Force Research Laboratory's Sensors Directorate (AFRL/SN).[2]

Meanwhile, technology had moved on from primitive radio altimeters in the 1930s to the first radar sets in World War II to more specialized and technically complex radars in the immediate postwar period. The invention of the first solid state electronic devices in the eleven years between 1948 and 1959, in turn, revolutionized electronics and all electronics-based capabilities, like radar. The application of solid-state electronics to computing, from the 1960s through the present day, has, in turn, allowed the programming and coordination of numerous electronics sensors and weapon systems with the purpose of detecting, tracking, and annihilating targets of interest in the ground-air-space battlefield of modern warfare.

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[1]   Book, Tom D. Crouch, *Wings: A History of Aviation from Kites to the Space Age* (New York and London: W. W. Norton, 2003), p. 153.

[2]   Study, Dr. James F. Aldridge, ASC/HO, "A Historical Overview of the Mission and Organization of the Wright Laboratory, 1917-1993," Nov 1994, pp. 16-17.

The most recent capability in targeting and surveillance added to the U.S. arsenal was the Joint Surveillance Target Attack Radar System (JSTARS). The JSTARS program was managed jointly by the U.S. Air Force and the U.S. Army. The program was first undertaken in the 1980s, as synthetic aperture radar (SAR) and moving target indication (MTI) technologies matured.

The JSTARS concept was born nearly a decade before, in the 1970s. The operational requirement from which it arose was the potential clash of Warsaw Pact and NATO forces on the continent of Europe, particularly in the area of the so-called "Fulda Gap." While NATO leadership was confident of assessing the strength and countering the first echelon of Warsaw Pact forces, i.e., those closest the front line of conflict, it was much less certain of determining the strength and disposition of second and third echelon forces as these moved forward to reinforce the first echelon.[3] This uncertainty arose over how enemy columns would typically advance and rest. Nothing in the U.S. arsenal at the time, neither SR-71s, nor U-2s, nor RF-4s, had sufficient persistence over the battlefield area to maintain a 24/7 surveillance of enemy troop and materiel movements. Consequently, it was very difficult to judge the size and tactics of the enemy's forces when "dug in" and camouflaged. Information was consequently episodic and partial—and thus clearly insufficient.

It was for this reason that the Defense Advanced Research Planning Agency (DARPA) initiated a study called "Assault Breaker" in the early 1970s.[4] DARPA's agent within the Air Force for managing "Assault Breaker" was the Rome Air Development Center (RADC), Rome, New York.[5] Under "Assault Breaker" a

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[3]   Intvw, Floyd P. Johnson, AFRL/SNZ, with Dr. James F. Aldridge, AFRL/HO, 28 Nov 05; Briefing, Floyd "Paul" Johnson, AFRL/SNZ, "Synthetic Aperture Radar (SAR) Heritage: An Air Force Perspective," 49th Annual Tri-Service Radar Symposium, Boulder, Colorado, 23-27 Jun 2003, n.d.

[4]   Chart, n.a., "Assault Breaker Engagement Scenario," n.d.

testbed was developed that integrated synthetic aperture radar (SAR) with a new radar capability: a slow ground moving target indicator (GMTI) radar that would be able to detect and target enemy troop movements on the way to the battlefront. This capability was called the Target Acquisition and Weapons Delivery System (TAWDS) and the program which managed it was called Pave Mover.[6]

The operational Air Force did not immediately recognize or seize upon the SAR and MTI capabilities demonstrated by Assault Breaker. The program was thus a classic case of "technology push" rather than "requirements pull." In fact, not till nearly a decade later, in the mid 1980s, were the Air Force's and Army's acquisition communities given the nod to begin the process of developing an operational weapon system equipped with integrated SAR and MTI, what came to be known as the "Joint Surveillance Target Attack Radar System" (Joint Stars or JSTARS).[7]

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[5]   RADC (cst. 1951) was reorganized and renamed the Rome Laboratory, in 1990. In 1997, the Air Force Research Laboratory (AFRL) was established and Rome Laboratory was disestablished. Its information technologies work became part of AFRL's Information Technology Directorate (AFRL/IF) and its sensors work became part of AFRL's Sensors Directorate (AFRL/SN). AFRL/SN was headquartered at Wright-Patterson AFB, OH; however, most of the Rome Laboratory's sensors experts remained at Rome where AFRL/IF was also headquartered. See Book, Thomas W. Thompson, *The Fifty-Year Role of the United States Air Force in Advancing Information Technology—A History of the Rome, New York, Ground Electronics Laboratory*, Studies in Twentieth Century American History, vol. 10 (Lewiston, Queenston, Lampeter: The Edwin Mellen Press), n.d., chapter 1; and History, ASC/HO, "History of the Aeronautical Systems Center, FY 1997," vol. 1, May 1998, pp. 247-8. RADC's John Entzwinger was program manager for "Assault Breaker." He later became the technical director of the Defense Airborne Reconnaissance Organization (DARO). See Intvw, Johnson with Aldridge.

[6]   Intvw, Johnson with Aldridge; Chart, n.a., "Target Acquisition—Weapon Delivery System (TAWDS)," n.d.

[7]   The Air Force agent for developing and acquiring JSTARS was the Electronic Systems Division/Center, Hanscom AFB, MA. Intvw, Johnson with Aldridge.

JSTARS was a complex system consisting of both airborne and ground elements. These elements were Air Force E-8C aircraft,[8] each equipped with a multi-mode radar system, and Army mobile ground station modules (GSMs). The E-8C aircraft continuously surveyed the battlefield at stand-off distances and relayed information real time to the GSMs, which called in weapon strikes. The weapons deployed during strikes were themselves complex, generally consisting of canisters containing various submunitions that were, in turn, programmed and/or guided to various specific targets, particularly enemy armor. JSTARS thus performed for ground forces what AWACS[9] did for air forces.[10]

JSTARS began flight testing in April 1988. Although still in development, it was deployed operationally for the first time during Operation Desert Storm (1991). In 1996, JSTARS was approved for full rate production. The initial buy consisted of 14 aircraft the last of which was delivered in August 2002. Three further aircraft were subsequently ordered and delivered between February 2003 and March 2005. In 1997, the Air Force awarded Northrop Grumman two contracts to replace the JSTARS computer system with a new system incorporating the latest commercial off-the-shelf (COTS) technology.

Meanwhile, the Air Force began planning for the next generation JSTARS under the Radar Technology Insertion Program (RTIP). The upgraded JSTARS

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[8] A modified version of the Boeing 707-300B aircraft. Northrop Grumman, which was the prime contractor for JSTARS, performed the modification and installed all electronics. See Article, n.a., "JSTARS Joint Surveillance and Target Attack Radar System, USA" [hereafter cited as "JSTARS"], n.d., at www.airforce-technology.com/project_printable.asp?ProjectID+1117, as of 28 Nov 05.

[9] AWACS = Airborne Warning and Control System. See Dictionary, Bill Gunston, *Jane's Aerospace Dictionary* (London, New York, Sydney: Jane's), 1980, p. 44.

[10] Intvw, Johnson with Aldridge.

was to have a much more powerful radar, an electronically scanned 2-D X-band active aperture phased array. The radar was to have a helicopter detection mode and inverse SAR (ISAR) imaging capability as well as an MTI mode that would allow real time imaging of moving targets.[11]

Farther over the horizon were two additional systems, one operating in the endoatmosphere, one in the exoatmosphere. The former was styled Sensor Craft. Sensor Craft was conceived as blending together various sensor modes into one platform including MTI, aerial surveillance, measurement and signature intelligence (MESINT), and signal intelligence (SIGINT) capabilities.[12] (JSTARS, by contrast, was almost entirely an MTI system. It could perform SAR missions, but this was not its principal activity or purpose.)[13] The second system was Space Based Radar. The Space Based Radar was best thought of as a "JSTARS in space." The Space Based Radar faced both technological challenges and geopolitical hurdles concerning the "weaponization" of space.[14]

[11]   See "JSTARS."

[12]   Intvw, Johnson with Aldridge; Brochure, "Sensor Craft: 'The Ever-present Eyes and Ears of the Warfighter'," n.d.

[13]   Intvw, Johnson with Aldridge.

[14]   Intvw, Johnson with Aldridge.

Kalman Filter and Its Impact

Many feel that the results of basic research take many years, if not decades, to come to fruition. On numerous occasions quite the opposite has occurred, and the Kalman Filter is one example where the end result of the basic research grant went directly to significant real world applications.

This story begins in the post-World War II era, when, with the advent of the jet age and supersonic flight, aircraft required more advanced and sophisticated navigation and flight control mechanisms. Thus, through the mid-1950s and early 1960s, the Air Force Office of Scientific Research (AFOSR) sponsored various research efforts in the area of control theory relating to high-speed aircraft, aerospace vehicle systems, and advanced space systems.[1] Aircraft designers had an ever increasing requirement to maintain aerodynamic integrity of their aircraft designs due to the ever increasing speeds of the airframes. This was especially acute for maintaining guidance and navigation accuracy.[2]

This problem, which had been plaguing guidance and navigation systems during the early and mid-1950s, was taken up by AFOSR. The issue was deriving the best information out of numerous and continuous data streams that inherently contained imprecise data. Throughout the 1950's, AFOSR sponsored several efforts in this area, including pioneering support of research in nonlinear systems. But in particular, it was AFOSR support given to the Research Institute for Advanced Studies (RIAS), in Baltimore, Maryland, that ultimately resulted in a solution. RIAS was established in 1957 in response to the Soviet Union's

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[1] AFOSR Discoverer database and DTIC science and technology research report database searches relative to "Control Theory" yield numerous results relating to optimizing avionic system configuration efforts.

[2] Brfg slide, n.a. [AFOSR/CC], "AFOSR Sponsored Research to Improve Guidance and Navigation Accuracy," Feb 2001, *Air Force Basic Research Success Stories*, slide 3.

launching of the first satellite, and was "perceived to be the center of the world in control theory." One historical sidelight to the AFOSR/RIAS relationship was the close proximity of the two organizations. At this time (1958) AFOSR was located in downtown Baltimore, Maryland, relatively close to RIAS, which of course, facilitated coordination and communication to attack this problem.[3]

AFOSR also initiated this support to investigate the use of modern mathematical statistical methods in estimation. AFOSR program managers perceived this opportunity for the creation of new mathematical techniques as one that could alter control applications, and they were well aware of the talented mathematician that could address this issue.[4] Dr. Rudolph Kalman, the primary principal investigator who would take up this challenge, had been supported by AFOSR since 1954 at the Massachusetts Institute of Technology. At MIT, Kalman addressed the mathematical issues of automatic control systems, before moving on to RIAS.[5]

The AFOSR-sponsored RIAS program that addressed the aerodynamic data integrity issue involved the development and application of statistical filtering theory under the direction of Kalman and Dr. Richard Bucy. Initially, only Dr.

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[3] Monograph, n.a., AFOSR, Office of Aerospace Research, AFOSR Document 67-0300, "AFOSR Research: The Current Research Program and Summary of AFOSR Research Accomplishments" [hereafter cited as "AFOSR Research"], Oct 1967, p. 101; Web article, Doug Peterson, University of Toronto, "An Engineering Odyssey," June 2005, at http://www.csl.uiuc.edu/faculty/wonham.asp as of 11 Sept 05.

[4] Monograph, Dr. Robert White, et al., AFOSR/PIC, "A Foundation for the Future: Celebrating 50 Years of Basic Research," Apr 2002, pp. 5, 7; Article, Col Robert B. Kalisch, USAF, "The Productivity of Basic Research," *Air University Review*, vol. 21, No. 1, Nov-Dec 1969.

[5] Database document, n.a. [Defense Technical Information Center], "Citation: Kalman, Rudolph E., Phase-Plane Analysis of Automatic Control Systems Containing Nonlinear Gain Elements," 1 July 1954.

Kalman addressed the problem, and in relatively rapid fashion, he solved a discrete portion of the data integrity issue with a paper entitled, "A New Approach to Linear Filtering and Prediction Problems."[6] With continued AFOSR support, Drs. Kalman and Bucy, then of the Johns Hopkins Applied Physics Laboratory, wrote several papers that ultimately led to the development of the Kalman Filter.[7] The Kalman linear filtering technique was developed in the years 1959-1961, with Bucy joining the effort in 1960.[8] This effort to eliminate unwanted noise out of a stream of data revolutionized the field of estimation and had an enormous impact on the design and development of precise navigation systems. "The net result is an algorithm tailored to real-time applications, where data keep coming in and decisions have to be made on the spot."[9] The Kalman and Bucy technique of combining and filtering information from multiple sensor sources achieved accuracies that clearly constituted a major breakthrough in guidance technology.[10]

Dr. Kalman's innovative algorithm eventually made the transition from a relatively abstract theory to practical application—especially for the nation's space program. The National Aeronautics and Space Administration embraced the Kalman Filter to solve the problems associated with determining satellite orbits. It quickly became a basic building block of the space program and was first used in the Ranger, Mariner, and Apollo missions of the 1960s. In particular,

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[6] Article, Barry Cipra, "Engineers Look to Kalman Filtering for Guidance" [hereafter cited as "Engineers Look"], *SIAM News,* vol. 26, No. 5, Aug 1993, p. 1.

[7] *Ibid.*

[8] Web article, Greg Welch, University of North Carolina at Chapel Hill, "Rudolph Kalman," May 2004, at: http://www.cs.unc.edu/~welch/kalman/siam_sontag.html as of 11 Sept 05; "Engineers Look."

[9] *Ibid.*

[10] "AFOSR Research," p. 102.

the Kalman Filter guided the Apollo 11 lunar module to the moon's surface.[11] The Kalman Filter quickly found its way into other operational systems such as phased-array radars to track missiles, sonar ranging, inertial guidance systems in aircraft (from the C-5 to the F-22 to the Boeing 777), submarines, missile autopilots, the Global Positioning System, the Space Shuttle, and rockets. The Kalman Filter has made possible the ubiquitous auto-pilot of both commercial and military aircraft, and its employment in Precision Guided Munitions has had a profound impact on the warfighting capabilities of the United States Air Force.[12]

Following the initial success of the Kalman Filter application to the space program in the 1960s, AFOSR continued to fund Kalman on a variety of studies up through 1988. A 1964 AFOSR research contract dealt with "Mathematical Techniques Basic to Optimum Avionic System Configuration." This study analyzed the future necessity of integrating all navigation, fire-control, and terrain following systems on Air Force fighter aircraft around digital processors.[13] Similar studies concerning various aspects of aerodynamic control, and aircraft identification systems followed.[14] In the 1970s, during which Dr. Kalman was supported by various AFOSR research grants, he played a major role in the

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[11] "Engineers Look."

[12] *Ibid.*

[13] Database document, n.a. [Defense Technical Information Center], "Citation: Kalman, Rudolph E., Mathematical Techniques Basic to Optimum Avionic System Configuration," Oct 1964.

[14] Database document, n.a. [Defense Technical Information Center], "Citation: Kalman, Rudolph E., Control Theory, Irreducible Realizations, Network Analysis Theory," 1 Feb 1965; Database document, n.a. [Defense Technical Information Center], "Citation: Kalman, Rudolph E., Mathematical Techniques for System Realization and Identification," June 1976.

introduction of algebraic and geometric techniques in the study of linear and nonlinear control systems.[15]

While the Kalman Filter is used in just about every inertial navigation system employed today, there are some very futuristic applications as well that are on the drawing boards.   One possible use, "…still well in the future, is in the 'smart' highway systems that will eventually orchestrate the smooth movement of cars at high speeds in tightly bunched (read: tailgating) groups known as platoons…a natural problem just begging for a Kalman Filter." [16]

Almost all modern control systems, both military and commercial, use the Kalman Filter, which, in essence, has revolutionized the mathematical field of estimation. In recognition of his unique work, Kalman was elected to the National Academy of Sciences in April 1994, and as one of his admirers remarked: "The paradigms formulated by Kalman and the basic results he established have become an intrinsic part of the foundations of control and systems theory and are standard tools in research as well as in every exposition of the area, from undergraduate engineering textbooks to graduate-level mathematics research monographs."[17]

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[15]   Database document, n.a. [Defense Technical Information Center], "Rudolph Kalman and AFOSR," Sept 2005; "Engineers Look," p. 3.

[16]   "Engineers Look."

[17]   *Ibid.*

Manufacturing Technology of Electronics Materials

Modern aviation electronics (= avionics) is based upon a handful of technical breakthroughs in the decades following World War II. The solid state transistor, the integrated circuit, the laser and associated electro-optical technologies, were all innovations of the postwar period. Just as important as the scientific breakthroughs that made these innovations possible were engineering and manufacturing processes that made them and the devices and systems derived from them available for military and, in many cases, commercial use. The organization responsible for sponsoring advances in the manufacturing of materiel for the Air Force is the Materials and Manufacturing Directorate of the Air Force Research Laboratory (AFRL/ML) and its predecessor organizations, primarily the Air Force Materials Laboratory (AFML).[1]

One of the most important areas of manufacturing science and engineering over past half century is that of semi-conductor materials and devices, the foundation of solid-state electronics.[2]

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[1]   The Air Force Manufacturing Program was established in 1947 in the Air Material Command (AMC), which became the Air Force Logistics Command (AFLC) in 1961. The Manufacturing Technology mission was transferred to the Materials Laboratory from AFLC, in 1962. In 1988, the Materials Laboratory's Manufacturing Technology Division was made a separate directorate under the Wright Research and Development Center (WRDC) and remained separate under the Wright Laboratory (1990-1997). With the formation of the Air Force Research Laboratory (AFRL), in 1997, the Materials Directorate was remerged with the Materials Laboratory to form AFRL's Materials and Manufacturing Directorate. See Study, James J. Niehaus, Air Force Materials Laboratory, "Five Decades of Materials Progress, 1917-1967," 4 Dec 67, pp. 112-113; Study, Dr. James F. Aldridge, ASC/HO, "A Historical Overview of the Mission and Organization of the Wright Laboratory, 1917-1993," Nov 1994, p. 24.

[2]   See Article, Donald Long, Honeywell Corporate Research Center, "Semiconductor," *Encyclopedia Americana*, International Edition (Danbury, Connecticut: Grolier), 2000, vol. 24, pp. 536-538.

Electronics was revolutionized in the dozen years between the invention of the first solid-state transistor, in 1947, and the invention of the first integrated circuit (IC), in 1959. Solid state devices were smaller, more compact, required less energy, and generated less heat than vacuum tubes that had ruled the world of electronics since the late 19th century. Needing more compact and reliable electronics devices for ballistic missiles, the U.S. military generously funded development of the new technology and in the early years, at least, was the solid state electronics industry's principal customer.[3]

The Air Force's Manufacturing Technology (ManTech) program, begun the year of the invention of the solid state transistor (1947), was a principal sponsor of advanced processes for solid-state materials manufacturing by the new microelectronics industry. The ManTech program, for example, underwrote the processing of high purity silicon, the most pervasive early semi-conductor material, and conducted pioneering work in the growth of silicon carbide crystals. ManTech promoted efforts to make the manufacture of solid state devices— initially very labor intensive—more efficient and economical. ManTech introduced automation and inspection technologies, including the use of scanning electron microscopes for in-process control.[4] ManTech provided early support of electronic packaging to provide hermetic sealing at the IC level and introduced the plastic packaging of ICs, which was adopted in the commercial sector. ManTech also studied multi-function IC packages.[5]

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[3] Report, n.a., "Air Force Manufacturing Technology: An Innovative Electronics Program—A Historical Perspective, 1962-1999" [hereafter cited as "Manufacturing Technology"], n.d., [p. i].

[4] Background paper, n.a., [Bob Denison, AFRL/MLPS], "History of Sensor Materials Technology in ML [Materials Directorate] and its Predecessors" [hereafter cited as "Sensor Materials"], 25 Jul 02, p. 2, and "Manufacturing Technology," [p. 4].

[5] "Manufacturing Technology," [pp. 7ff].

All this was initiated during the 1960s. In the 1970s and 1980s, ManTech provided up-front funding for a new industry sector concerned with projection mask processing for integrated circuits.[6] ManTech underwrote development and manufacture of metal oxide semiconductor field effect transistors (MOSFETs) that soon replaced the junction transistors of the 1960s.[7] It continued to support technologies and processes for manufacturing integrated circuits. During the 1970s, it supported Very High Speed Integrated Circuit (VHSIC) technologies and Very Large Scale Integrated Circuits (VLSICs) that were then being introduced. This support continued through the VHSIC revolution of the 1980s.[8]

The Air Force soon mounted a major effort to develop semiconductor materials with better electrical qualities than germanium and silicon, the two earliest solid state substrate materials. As early as the 1950s, the Air Force Materials Laboratory had begun research into Gallium Arsenide (GaAs) as a substrate material. GaAs device technology was reaching maturity in the 1970s, and beginning in 1980s, GaAs devices were produced in quantity. The ManTech program supported the GaAs manufacturing effort, including "growing" high quality and low defect GaAs crystals by improving the Czochralski manufacturing process.[9] In the 1980s and 1990s, work on GaAs material production and device manufacture was followed by research into the potential of Indium Phosphide (InP) and Gallium Nitride (GaN) as follow-on materials to GaAs.[10]

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[6]   "Manufacturing Technology," [p. 7].

[7]   "Manufacturing Technology," [p. 17].

[8]   "Manufacturing Technology," [p. 7].

[9]   History, ASD/HO, "History of the Aeronautical Systems Division, CY 1986," Part II: "History of the Air Force Wright Aeronautical Laboratories, CY 1984-1986," July 1987, vol. 1, p. 86.

[10]   "Sensor Materials," [p. 2].

Applications of solid state electronics devices contributed to the success of the ICBM, MILSTAR, Small ICBM, Space Systems (rockets and satellites), Maverick, Advanced Medium Range Air-to-Air Missile (AMRAAM), Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) pod, B-1B, F-16, PAVE PAWS, et al.[11]

The invention of the laser[12] in 1960 substantially enlarged the menu of potential weapon system capabilities. The first lasers utilized ruby crystals to produce the coherent light of the laser beam. Almost immediately following the appearance of the laser, the Air Force Manufacturing Technology program undertook to improve the growth of ruby crystals. ManTech also underwrote development of other laser materials, including Gallium Arsenide-Gallium Phosphide (GaAs-Ga-P) crystals, paying particular attention to epitaxial growth processes of the material. Within a decade after the invention of the laser, the U.S. Air Force was employing laser guided bombs in Vietnam, with devastating effect.[13]

In addition to IC and laser technologies, the Air Force Manufacturing Technology program in the period since the 1980s made major contributions to manufacturing science and processes for electro-optical materials, including detectors, inertial navigation, displays, and other electro-optical devices. ManTech likewise supported the development and manufacture of traveling wave tubes, solid state devices, and transmit/receive modules for solid state phased

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[11] "Sensor Materials," [pp. 3-4].

[12] The term "laser" was, in fact, an acronym for "light amplification by simulated emission of radiation." See Article, Donald F. Nelson, Bell Laboratories, "Laser," *Encyclopedia Americana*, n.d., vol. 16, pp. 772-777.

[13] Report, Dr. James F. Aldridge, ed., ASC/HO, "USAF Research & Development: The Legacy of the Wright Laboratory Science and Engineering Community, 1917-1997" [hereafter cited as "USAF R&D"], 1997, pp. 89-90.

array radars.[14] Finally, ManTech developed better manufacturing processes for battery cells, solar cells, and aircraft and spacecraft power supplies.[15]

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[14] ManTech achieved considerable success in reducing the production costs of transmit/receive modules for solid state phased array radars, primarily by supporting the development of monolithic integrated circuits vice hybrid circuits. This success allowed the use of advanced phased array radars in the F-22. "USAF R&D," pp. 161-164.

[15] "Manufacturing Technology," [p. 2].

Maser to Airborne Laser

It is a little appreciated fact outside of the scientific community the degree to which the fruits of basic research permeate our lives.   In the case of the MASER (Microwave Amplification by Stimulated Emission of Radiation), which was alternatively dubbed by its critics as "Means of Acquiring Support for Expensive Research," it has led to an airborne laser weapon system with the potential to shoot ballistic missiles out of the sky. When the theory for the MASER was initially conceived, such a weapons application was never imagined.[1]

Dr. Charles Townes, who is widely regarded as the father of the laser, first had the idea for the MASER in 1951, but at the time did not have the funding to pursue it. It was only in 1953, when Townes moved to Columbia University, that he received AFOSR funding to "...work on the interaction of waves...especially experimental observation of optical spectra."[2]

The research that Dr. Townes was involved with prior to 1951 prepared him well for what lay ahead. Following World War II, scientists concentrated on developing radar equipment that used increasingly shorter wavelengths. Townes took part in this endeavor with the Joint Services Electronics Program (JSEP), which was established in 1946, and joined by the Air Force in 1947 to support former wartime laboratories, including the one at Columbia University. Initially, the challenge was to develop shorter wavelength systems to enable better directivity for aircraft and to use smaller antennas. Then, Townes turned his attention to applying the microwave technique of wartime radar research to spectroscopy. He foresaw this research as providing a powerful new tool for the

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[1]   Interview, Dr. Charles Townes, University of California, Berkeley, with Erin Crawley, AFOSR/PIC, 6 Oct 2005.

[2]   *Ibid.*

study of the structure of atoms and molecules and as a potential new basis for controlling electromagnetic waves.[3]

Townes' follow-on work to the initial 1951 MASER concept involved working on a device using ammonia gas as the active medium, and in early 1954, he obtained the first amplification and generation of electromagnetic waves by stimulated emission and coined the word "MASER" for this device. AFOSR first began funding Dr. Townes in January of 1953 and continued to do so well into the 1960s.[4] That funding paid off handsomely, because the next step in the basic research chain made way for the LASER. It was on 15 July 1958 that Dr. William J. Otting, then Director of AFOSR's Physical Sciences Directorate, received a proposal from Dr. Townes to do research "...on a device to produce 'LASER' radiation.[5] According to Dr. Otting, the proposal received technical and administrative approval "within two or three days, and was hand carried to the Procurement Division for the preparation of a research contract as soon as possible."[6] The AFOSR contract, No. 49 (638)-507, was issued on 15 September 1958, and accepted by Columbia University on 16 October 1958. The title of the research contract was "Research on a MASER to Amplify or Oscillate at Infrared Frequencies."[7]

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[3]   Interview, Townes with Crawley; Interview, Dr. Howard Schlossberg, AFOSR/NE, with Dr. Bob White and Nahaku McFadden, AFOSR/PIC, 14 February 2002; Web article, Howard Schlossberg, AFOSR/NE, and Robert White, AFOSR/PIC, "The Development of the Laser" [hereafter cited as "Development"], *AFRL Technology Horizons*, Mar 2002, at: http://www.afrlhorizons.com/Briefs/Mar02/DE0106.html as of 26 Oct 05.

[4]   Bio, n.a. [AFOSR/NI], "AFOSR Nobel Laureates: Dr. Charles Townes," n.d. [1971]. During this period Dr. Townes also received funding from the Navy Research Office and Army Research Office as well. See: Interview, Townes and Crawley.

[5]   Letter, William J. Otting, AFOSR/NA, to Dr. Joseph Janni, AFOSR/CC, untitled, 27 Dec 1999.

[6]   *Ibid.*

[7]   *Ibid.*

In collaboration with Dr. Art Schawlow, work was begun on a theory that would enable operations at wavelengths a thousand times shorter than the MASER. In December 1958, Drs. Schawlow and Townes published the principles for the LASER in *Physical Review*.[8] Work continued on the LASER by various researchers during this period and a patent was issued to others in 1960. Ultimately, in 1964, Townes, along with Drs. Alexander Prokhorov and Nikolai Basov, of the Lebedev Institute in Moscow, shared the Nobel Prize in physics for their work on the maser/laser principal. Dr. Schawlow was so honored in 1981.[9]

At the time AFOSR was funding Drs Townes and Schawlow, it was also supporting Professors Chihiro Kikuchi and J. Lambe—two future Nobel laureates in physics—with a 1956 research grant that investigated the electron-spin resonance properties of synthetic ruby; and it was on 20 December 1957 that Kikuchi's team at the University of Michigan Willow Run Laboratories produced the first indication of maser action in a synthetic ruby crystal.[10]

This critical discovery led to the development by others of the ruby maser. But laser research by the late 1950s had also branched out into the development of chemical lasers. Such was the case with AFOSR funding for John Polanyi—

[8] Web article, A.L. Schawlow, Columbia University and C.H. Townes, Bell Telephone Laboratories, "Infrared and Optical Masers," *Physical Review*, vol. 112, Issue No. 6, 15 Dec 1958, pp. 1940-1949, at: http://link.aps.org/abstract/PR/v112/p1940 as of 4 Nov 05.

[9] "Development."

[10] Chronology, Historical Division, Office of Information, Office of Aerospace Research, "Office of Aerospace Research Chronology, 1945-1968," July 1968, p. 17; Article, C. Kikuchi, et al., University of Michigan Engineering Research Institute, "Maser Action in Ruby," *Physical Review*, Vol. 109, Issue 4, 15 Feb 1958, pp. 1399-1400.

another Nobel laureate in physics—which began in 1956.[11] Polanyi's AFOSR-funded research was instrumental in moving forward in the chemical laser realm in the area of the hydrogen fluoride (HF) and iodine atom photodissociation lasers, and he was the first to postulate that certain chemical reactions would result in excited lasing products.[12] By 1960, work on the laser was well in hand by a variety of researchers—and one of these AFOSR-funded physicists, George Pimentel, was responsible for the discovery of the first true chemical laser.[13]

Working under AFOSR contract number AF 49 (638)-1, dated 1 September 1956, George Pimental and J. V. Kasper at the University of California, Berkeley were the first to detect infrared chemical laser emissions and in 1965 demonstrated the first iodine (chemical) laser—termed a photolysis laser—due to the fact that an intense flash of light initiated the requisite chemistry that excited iodine atoms to lase. At its most basic level, the iodine laser was a precursor to the Chemical Oxygen Iodine Laser (COIL).[14] Pimentel's own words are testament to the surprising nature of basic research:

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[11] Interview, Dr. Michael Berman, AFOSR/NL, with Dr. Bob White, AFOSR/PIC, 15 Sept 2005; Speech, Dr. Michael Berman, AFOSR/NL, "Historical Perspectives on Basic Research and the Development of High Power Chemical Lasers," n. d., p. 1.

[12] Interview, Berman and White; Article, M.C. Liu, M.E. Umstead, and N. Djeu, Naval Research Laboratory, "Chemical Lasers," *Annual Review of Physical Chemistry* [hereafter cited as "Chemical Lasers," *ARPC*], vol. 34, Oct 1983, pp. 557-591.

[13] Paper, Denton W. Elliott, AFOSR/SRC, "Dr. George C. Pimentel," 18 June 1970; Nomination citation, Donald L. Ball, AFOSR/NC, "Nomination for the National Medal of Science," 12 Apr 1976, p. 4.

[14] AFOSR contract file, AFOSR/NC, "G. C. Pimentel: Infrared Spectra of Free Radicals and Unstable Intermediates," 1 Sept 1956, p. 4; Interview, Berman and White; "Chemical Lasers," *ARPC*, pp. 557-591; Article, George C. Pimentel, "Chemical Lasers," *Scientific American* [hereafter cited as "Chemical Lasers," *SA*], Apr 1966, pp. 32-39; Letter, Amos G. Horney, AFOSR/SRC, to Dr. William J. Price, "American Chemical Society Award for Creative Invention," 2 Feb 1967.

The intent was to search for vibrational excitation in the CF_3 fragment produced by photolysis...Kasper measured the frequency of the intense bursts and found that the emitter was not CF_3 as we had sought and expected, but the iodine atom! The reaction was producing this atom preferentially in a state of electronic excitation....Here, then, was the discovery of the first photodissociation laser.[15]

Having demonstrated the first chemical laser, AFOSR's next step was to improve on it. This was done through AFOSR's continued funding of Professors Polanyi at the University of Toronto, and Dudley Hershbach of Harvard. Their efforts provided critical insight concerning the disposition of energy in chemical reactions as it related to the laser. For their efforts they were awarded the Nobel Prize in Chemistry in 1986.[16] The research surrounding a chemical laser's creation and disposition of energy dealt with primarily one issue, and that was weight, and by extension, size. For the advantage of an efficient chemical laser to the Air Force meant the possibility of a practical weapons application. As a circa 1966 AFOSR staff study concluded:

Now that the chemical laser is a reality, it remains only for further research to find either more powerful laser-producing reactions, or to discover a chemical reaction which can give multiple flashes for other practical applications of Air Force interest.[17]

The research to make this concept a reality took a while, and basic research made it happen—the result was the first COIL lasing demonstration in 1977.[18] But in the interim, AFOSR-funded research led to the first continuous wave HF

[15] "Chemical Lasers," *SA*, Apr 1966, p. 38.

[16] "Development."

[17] Paper, Dr. William L. Ruigh, AFOSR/NC, "New Methods and Techniques," n. d. [1966], p. 24.

[18] Letter, Steve Davis, Physical Sciences Incorporated, to Dr. Michael Berman, AFOSR/NL, 28 Apr 1997, p. 1; E-mail, Michael Berman, AFOSR/NL, to Howard Schlossberg, AFOSR/NE, "Laser refercnces," 9 Nov 1999; Monograph, William E. McDermott, Directed Energy Solution, Inc., "Historical Perspective on COIL" [hereafter cited as "COIL"], n.d.

laser in 1969 as well as the first demonstration of a purely chemical HF laser in the same year, and it was in 1972 that a seminal paper by R. G. Derwent and B. A. Thrush at Cambridge University paved the way for COIL.[19] Derwent and Thrush are generally credited with recognizing that a COIL laser was feasible, by providing the process by which the iodine atom can lase.[20] But Derwent and Thrush had help along the way. It was in 1966 that AFOSR-funded researcher Elmer A. Ogryzlo and his team at Brandeis University observed that when iodine was added to excited oxygen, a bright yellow glow was produced. In addition, they also observed a strong emission from the iodine atom transition, which was attributed to the resonant (pumping) action of O2 singlet delta.[21] This work did not attract the attention of the laser research community at the time. But in 1969 Ogryzlo began a sabbatical at Dr. Brian Thrush's laboratory at Cambridge and brought this knowledge with him. It was there that he suggested follow-on work be done on his 1966 oxygen-iodine experiments, which was pursued by Thrush's graduate student, R. G. Derwent. Thus, it was from Ogryzlo's earlier AFOSR-funded research that Derwent and Thrush's seminal paper had its

[19] Article, R. G. Derwent and B. A. Thrush, Cambridge University, "Excitation of Iodine by Singlet Molecular Oxygen," *Faraday Disc. Chem. Soc.,* vol. 53, Issue 162, 1972.

[20] Derwent and Thrush, taking their lead from the work of George Pimentel, understood that the hurdle was to create iodine atoms in the electronically excited state by some chemical means. It was known that the way one goes about this is by exciting oxygen molecules to an excited molecular state—which is called O2 singlet delta—and there are only certain chemical reactions that can produce O2 selectively in this excited state. Once achieved, the energy that is in this O2 singlet delta eventually gets transferred to the iodine atoms and makes it lase. Thus, if one can make this O2 singlet delta, in high yield, through a chemical process, one can make an efficient laser. See: Letter, Steve Davis, Physical Sciences Incorporated, to Dr. Michael Berman, AFOSR/NL, 28 Apr 1997, p. 1; Interview, Berman with White.

[21] "COIL," p. 1; Article, S. J. Arnold, N. Finlayson, and E. A. Ogryzlo, Brandeis University, et al, "Some Novel Energy-Pooling Processes Involving O2 singlet delta," *Journal Chem. Phys.,* vol. 44, 1966, p. 2529.

genesis.[22] These breakthroughs led to the Air Force development of chemical lasers focusing on direct chemical excitation laser systems such as the HF/DF MIRACL and ALPHA lasers.[23]

The key breakthroughs which facilitated the development of the COIL were made possible by the AFOSR-funded work of many researchers, but in particular, Elmer Ogryzlo's work in the mid-1960s was a significant turning point, leading to Derwent and Thrush's significant generation—greater than 15 percent—of O2 singlet delta in the excited state, which was critical to achieving the degree of lasing efficiency necessary relative to size, weight, and power for a weapons application. According to William McDermott (co-inventor with Nicholas Pchelkin of the COIL), the 1972 Derwent and Thrush paper "produced a considerable amount of interest at the Air Force Weapons Laboratory (AFWL)," predecessor to AFRL's Directed Energy Laboratory, at Kirtland AFB, NM. AFOSR had been providing consistent laser-related funding to AFWL for a decade previous, funding much of the early pioneering work on HF lasers.[24] Al McKnight, an AFWL advocate of short wavelength chemical lasers, brought the Derwent and Thrush article to McDermott's attention in 1973. McDermott had just arrived at AFOSR's Seiler lab at the USAF Academy, and his team was working on the O2 singlet delta issue. The team was working on singlet oxygen generators to make a chemical system that efficiently produces the O2 singlet delta state by chemical reaction—by mixing chemicals together.[25] In the next two years, with AFOSR funding, McDermott and his team enhanced the O2 singlet delta generator process, but then McDermott was absent from the effort

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[22] "COIL," p. 1.

[23] Outline, Dr. Michael Berman, AFOSR/NL, "Historical Perspectives on Basic Research and the Development of High Power Chemical Lasers," n. d., p. 1.

[24] "COIL," p. 2; Letter, Steve Davis, Physical Sciences Incorporated, to Dr. Michael Berman, AFOSR/NL, untitled, 28 Apr 1997, p. 2.

[25] Interview, Berman and White; "COIL," p. 2.

for a year attending an Air Force middle management school. He was then reassigned to AFWL, where, along with Nick Pchelkin, and Dave Benard, he first successfully demonstrated COIL lasing in 1977.[26]

In the words of Bill McDermott, "AFOSR-sponsored research in the mid-1970s was absolutely critical to the invention of the COIL. Not only did AFOSR sponsor my own first efforts to develop a chemical generator, but supported technical efforts throughout the world."[27] AFOSR support was not only critical to the development of the COIL, which was chosen to be used in the Airborne Laser (ABL), but AFOSR went on to fund numerous enhancements, to include: atmospheric compensation and correction work that enable 95 percent of the laser power to reach the target (1985); vibration elimination, which resulted in significant improvement in laser targeting (1988); and a water vapor sensor which resulted in a 20 percent increase in efficiency (1995). AFOSR-funded efforts improved COIL performance with research on the All Gas-phase Iodine Laser (AGIL), which provided twice the power of COIL, with half the weight.[28]

The talent and vision of numerous AFOSR program managers made ballistic missile defense a reality, but it all started with the promise that one AFOSR program manager saw in the work of Charles Townes. As Townes himself noted: "

> It was great that AFOSR supported that kind of general
> investigation with looking at new things. The [laser] came out of
> that work and the freedom of this funding was very important to that
> because we could explore all kinds of things. I think if somebody
> had tried to direct my work and say, 'Well we want you to [study]

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[26]   "COIL," p. 4.

[27]   "COIL," p. 6.

[28]   Brfg, Dr. Michael Berman, AFOSR/NL, "Basic Research Breakthroughs Enabled ABL," n. d.; Brfg, Dr. Michael Berman, AFOSR/NL, "AFOSR Supports Research Enabling and Improving the ABL," n. d., p. 9.

some type of new light source or something like that,' I would have never done the right thing at all. New science and new ideas are surprising. We never know how to predict them, we just have to explore...and AFOSR has supported that exploration.[29]

[29] Interview, Townes with Crawley.

Miniature Munitions Technology Demonstration[1]

The Small Diameter Bomb (SDB), soon to be introduced into the Air Force inventory, began in 1995 as the AFRL Munitions Directorate's (AFRL/MN) Miniaturized Munition Technology Demonstration (MMTD) Program. Later known as Small Smart Bomb, the program developed technologies for a 250-lb munition that would be effective against a majority of hardened and relocatable targets previously vulnerable only to 2,000-lb class penetrating munitions. One of the greatest benefits is a four-fold increase in weapon loadout for fighter and bomber aircraft. With each bomb independently targeted and autonomously guided, the number of targets killed for a single aircraft can be increased. Also the smaller volume and weight of miniature munitions means more munitions can be transported with our current logistics capability. This permits a much more rapid deployment of warfighting capability to the region of conflict. Another benefit is that the bomb's accuracy and lower explosive yield will focus the bomb's lethality on the target while reducing the potential for collateral damage.

The MMTD program demonstrated a basic small bomb capability between September 1995 and March 1997. This was a 250 pound class weapon with Differential Global Positioning System/Inertial Navigation System (DGPS/INS) and optimal guidance laws to achieve precision accuracy and optimal attitude at impact. Five guided drops were completed with an average miss distance of 2.2 meters against surveyed targets. Release conditions varied from 0.80 mach/30K feet altitude to 0.97 mach/40K feet altitude. Target ranges varied between approximately 5.5 to 12 nautical miles and the time of flight was from 50 to 99 seconds. These drops demonstrated the capability to simultaneously achieve accuracy, impact angle, angle of attack, and impact velocity to ensure target penetration, warhead case survivability and munition effectiveness. This

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[1]   The following article was contributed by personnel from AFRL's Munitions Directorate. They are Frank Christopher, AFRL/MNAV; Frederick Davis, AFRL/MNA; and Michael Duvall, AFRL/MNAV.

effectiveness was validated against a broad range of targets, to include buried, hardened aircraft shelters. The MMTD case design incorporated a tri-conic nose which enabled penetration of six feet of reinforced concrete. With less than 50-lbs of explosive, MMTD demonstrated in 1997 the ability to defeat hardened targets without collateral damage. The mitigation of collateral damage was enabled by the increased accuracy which reduced the lethal radius required to defeat the target, and therefore reduced the required explosive yield. AFRL also developed a Hard Target Smart Fuze for real-time detection/counting of voids within hard targets to detonate the warhead at a precise location.[2]

MN also successfully completed the Small Smart Bomb Range Extension (SSBREX) program in 2000, which developed a compact wing kit that could be stowed during aircraft carriage to maintain high aircraft loadout. This demonstration used the MMTD as a baseline capability and incorporated a folding wing kit. The wing kit, which deployed after launch, provided a 35 nautical mile standoff or a 20 nautical mile off boresight capability that maintained the penetration capability of the weapon. This expanded footprint allowed a single release point for multiple munitions which simplified mission planning, expanded the target area held at risk from a single aircraft, and minimized the amount of time an aircraft is exposed to hostile fire. Three guided flight tests were completed with release conditions from 0.85 mach/29K feet altitude to 0.90 mach/40K feet altitude. Standoff ranges varied from 18 nm downrange and 5 nm off boresight to 25 nm downrange and 4 nm off boresight, tripling the range of the small smart bomb. These SSBREX guided flight tests demonstrated wing opening, stability and control, significant range extension, and impact accuracy and velocity. This program also included the first U.S. demonstration of grid fin technology, which enabled more robust fin deployment in the dynamic flight environment and reduced battery requirements for extended range flights. The

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[2]   Report, AEDC/HO, "Miniature Munitions Technology Demonstration (MMTD) Phase I, September 1995 – March 1997," n.d.

lattice fin technology was used on the Massive Ordnance Air Blast munition in 2002.[3]

Another complementary MN program was the Small Munition Dispenser (SMD) Demonstration from FY99 to flight testing in FY02. Its purpose was to develop and demonstrate a dispensing system for miniature munition concepts like Small Smart Bomb and the Low Cost Autonomous Attack System, and for future miniature munition concepts. This program developed and flight tested advanced dispenser technologies such as the light weight dispenser structural design, high performance low maintenance ejector technology, and advanced electronics that allowed for eight or more stores to be initialized, targeted and managed through a single aircraft Mil-Std-1760 weapon station. This dispenser system was compatible with both fighters and bombers, supporting either internal or external carriage. This program also transitioned to the SDB acquisition program and will provide a critical capability for Air Force utilization of miniature munitions.[4]

The SDB program relied on AFRL/MN to develop new technology in many disciplines, such as fuzes, warheads, guidance and control, wing kits, dispenser and novel fin design. As General Ronald Yates prophetically stated in May 1995, "Small Smart Bomb could be a revolution in the future of air-to-surface warfare." Small Smart Bomb is now a reality. On 20 September 2005, Small Smart Bomb, now called Small Diameter Bomb, was certified to enter Operational Test and Evaluation. It is expected to be delivered to the field for operational use by Spring of 2006.[5]

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[3]   Article, Michael Duvall, AFRL/MNAV, "Small Smart Bomb Success Story," n.d.

[4]   *Ibid.*

[5]   Article, Frederick Davis, AFRL/MNAV, "Miniature Munitions Technology," n.d.

Modern Solid Propellant Rockets

The concept of a rocket propelled by the burning of a solid fuel was the earliest form of rocketry. The first Chinese rockets, which used black powder as a propellant, appeared over one thousand years ago, but it was not until centuries later when Europeans adopted the technology that solid rockets were first militarized. The famous "red glare" of the Congreve rocket referenced in "The Star Spangled Banner" signaled the first real advancements in the state-of-the-art, which was followed by subsequent experimentation with solid rockets for military use in several countries. At the turn of the 20th Century, a second wave of development made rockets practical. Robert Goddard in the U.S., Hermann Oberth in Germany, and Konstantine Tsiolkovsky in Russia theorized and experimented with rocket engines (both solid and liquid) in the early part of the century, but it was Wernher von Braun's German rocket team that designed and deployed the V-2 liquid rocket in World War II that made the use of rockets for air vehicle propulsion truly feasible.[1]

The US Army found interest in solid rockets for use as weapons and came to dominate the field in their use and production until well after the end of World War II. However, it was the Army's Air Corps that emerged as the service's focal point for employing rockets as a means of aircraft propulsion. For two decades, the Power Plant Laboratory (now AFRL/PR) and its predecessors, the Power Plant Branch and Power Plant Section, at Wright Field had been responsible for aircraft engine technology development, including various forms of advanced propulsion advocated by its innovative engineers and leaders. In 1939, the lab

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[1]   Article, Alain Davenas, "Development of Modern Solid Propellants" [hereafter cited as "Solid Propellants"], *Journal of Propulsion and Power*, vol. 19, no. 6 (Nov-Dec 03), pp. 1108-1109; Website, Dwayne Day, "U.S. Centennial of Flight Commission: Solid Propellants for Missiles and Rockets," available on the internet: http://www.centennialofflight.gov/essay/SPACEFLIGHT/solids/SP13.htm, as of 14 Jun 05.

began its first research, albeit on a very small scale, with rockets. Wartime exigencies provided a massive expansion of work in the labs, but the foremost emphasis was on traditional methods of propulsion that had immediate relevance to the forces in the field. That practicality meant that the Power Plant Lab's wartime work in rocketry focused on boosters for the Assisted Take-Off (ATO) of propeller planes.[2] Small liquid engine rockets (the regular army continued to monopolize solids) were strapped to the sides of various aircraft to shorten the amount of time and runway it took to get an airplane off the ground. Lab Technical Director Weldon Worth admitted that "These were not in any sense developed engines...The understanding, technique, and accomplishments of the Germans were far ahead of anything in this country." What technology the lab had was in fact based heavily on the Von Braun team's work, though it also arranged for the purchase of Goddard's patents. By 1946, the lab's rocket development program had expanded into applied research, component development, and testing of engines "for use as vehicle boosters, missile propulsion, primary aircraft power plants, and assisted take-off."[3]

The Air Force's earliest work on solid rockets was mainly restricted to limited development of Army and Navy rockets and was especially focused on improvements in propellants. Some of its early solids programs included turbine engine starter cartridges, JATO for early cruise missiles like Mace and Matador, and the early Falcon Guided Air Rocket. Ironically, it was a jet aircraft program that truly put the Power Plant Lab in the business of rocket development. Engine power of the proposed B-47 jet bomber was insufficient for the aircraft to take off

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[2]   The later term Jet-Assisted Take Off (JATO) is often a source of confusion, as it typically refers to methods of *rocket* assistance (RATO), not to *jet* (turbine) engines. However, in the context of the 1940s, "jet" generically cited any means of propulsion using reactive force, which included rockets, pulsejets, ramjets, and turbine engines.

[3]   Paper, Air Force Power Plant Laboratory, "Technical Accomplishments - Power Plant Laboratory, Fiscal Years 1946-1951," 3 Sep 51, pp. 29-56; Chart, Air Force Power Plant Laboratory, "Power Plant Laboratory Research and Development Obligations: FY 1942 thru FY 1951 Inclusive," 15 Jul 51.

under certain conditions, prompting the lab to investigate JATO methods, both liquid and solid. Major Edward N. Hall took charge of the latter efforts, turning to the Army first, but discovering that it had no inexpensive, high-performance rockets. Neither the Army nor Navy were cooperative in developing such a program, but for the Air Force cost was such an issue that it opted to "go into business for themselves." Weldon Worth, an important figure in early Air Force solid rocket work, had already searched for ways of decreasing the "prohibitive cost of solid propellant rockets," and in doing so, advocated the novel use of asphalt mixed with ammonium nitrate as a solid propellant, a mixture first devised at the Jet Propulsion Laboratory. That line of research ended by 1950 because of operating temperature limitations, but Hall's efforts by 1952 proved seminal in starting a new era both of Air Force solid rocket research and in propellant research by industry.[4]

The Power Plant Lab was at least in part hampered by their lack of suitable test facilities for rockets. The Dayton, Ohio, location of Wright Field and its proximity to a large civilian population kept the size of test stands down to the "backyard variety" insufficient for new, larger rockets. In 1947, the Air Force chose Leuhman Ridge in what was then Muroc Army Air Base (redesignated Edwards Air Force Base in December 1949), California, for the relocation of rocket testing and the construction of massive new static test stands. Work commenced on the site in 1949 and the first stands became operational in 1952. In 1959, following the post-Sputnik shake-up of military R&D, the Air Force chose to enhance its in-house rocket R&D capabilities and consolidate its experts from

4   Paper, R. Geisler, "My Memoirs of Solid Propellant Development at the Air Force Rocket Propulsion Laboratory" [hereafter cited as "My Memoirs"], AIAA Paper 93-1783, Jun 93, p. 2; Article, Leonard H. Caveny, et al., "Solid Rocket Enabling Technologies and Milestones in the United States" [hereafter cited as "Solid Rocket"], *Journal of Propulsion and Power,* vol. 19, no. 6 (Nov-Dec 03), p. 1045; Book, Roy Neal, *Ace in the Hole,* (Garden City, NY: Doubleday & Company, Inc., 1962), pp. 52-59, 66; Article, Howard Seifert, "Twenty-Five Years of Rocket Development," *Jet Propulsion,* vol. 25, no. 11 (Nov 55), p. 595; "Solid Propellants," p. 1111.

Wright Field with the test community at Edwards to form the Rocket Propulsion Laboratory (RPL, now AFRL/PRS). The formative years of the Rocket Propulsion Lab were the beginning of the space age and the space race. The first of a dozen or so test stands rose on Leuhman ridge to test key missile systems like the Navaho and Bomarc, but it was the rise of the first intercontinental ballistic missiles (ICBMs) that propelled solid rocket development at the Lab.[5]

Until the late 1950s, solid rockets were in the shadow of their liquid-fuelled counterparts when it came to strategic missile applications. Solids technology lacked in certain areas, such as casting large-diameter grains, and that limited their size to only a few thousand pounds of thrust. However, the liquid fuel missiles like Atlas were logistically difficult to deploy in numbers, protect from attack, and launch quickly. Those shortcomings, along with new and smaller nuclear warhead designs, gave Ed Hall, now a colonel under Bernard Schriever, the opportunity to successfully lobby for a solid-fuel ballistic missile within the Air Force. He envisioned a program to advance the state-of-the-art to make feasible a solid rocket ICBM. His efforts resulted in two programs that changed the field: the Air Force Large Solid Rocket Motor (LSRM) Program for technology development and, later, the Minuteman missile. Unfortunately for Hall, his organization prioritized the near-term liquid rockets, and gave up the LSRM program to the Wright Air Development Center, which included the Power Plant Lab, in 1956. The lab subsequently issued contracts to the major manufacturers of solid propellants to solve the key limiting problems of scaling up the motors.

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[5] Website, AFRL/PR, "History-Edwards Research Site," available on the internet: http://www.pr.afrl.af.mil/, as of 13 Jun 05; History, Edwards Air Force Base, "Semi-Annual History," Jul-Dec 1953, p. 150; History, Air Force Systems Command History Office, "History of the Air Force Rocket Propulsion Laboratory," 1 January, 30 June 1964, pp. 3-4; "Solid Rocket," pp. 1045-1046; History, Air Force Flight Test Center, "Semi-Annual History of the Air Force Flight Test Center," 1 January – 30 June 1958, n.d., pp. 14-3 – 14-5.

Those efforts, taken over by the Rocket Propulsion Lab in 1959, concerned "problems with long-duration firings of solid propellants, thrust termination, thrust-vector control, and the exposure of nozzles to the heat associated with high specific impulses," as well as methods of curing large solid propellant grains. The LSRM program put the RPL at the epicenter of large solid rocket development. The program produced the largest rockets to date, up to 13 feet in diameter, for technology demonstration purposes. The LSRM's most substantial contribution was the fostering of segmented solid rockets. It was clear that large diameter rockets were impractical to manufacture and transport, thus the need for some method of subdividing them became apparent. The RPL contracted with several companies to develop this technology, resulting in the first successful firings of segmented solid rockets. The LSRM program had an unexpected benefit: it pushed the rocket scientists at the lab to develop new tools for analysis and prediction, the precursors for modern computer modeling and simulation, and prompted a greater understanding of the chemistry behind propellants. DARPA's Project Principia provided significant funding to markedly improve rocket propellant chemical energies starting in the late 1950s. The RPL managed a sub-program that resulted in the creation of the "JANNAF Thermochemical Tables and related Isp computer programs to permit the accurate determination of theoretical propellant performance" that are still used world-wide.[6]

Though Hall lost the solid rocket technology development program to the labs, he did not give up on pushing the application to ballistic missiles and had successfully initiated the Minuteman missile by 1958. The success of the Large Solid Rocket program led directly to the Minuteman missile program. The first

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[6] *Ace in the Hole*, pp. 71-78; Article, J.D. Hunley, "The Evolution of Large Solid Propellant Rocketry in the United States," *Quest: The History of Spaceflight Quarterly*, vol. 6, no. 1 (Spring 98), p. 28; Paper, J. D. Hunley, "The History of Solid Propellant Rocketry: What We Do and Do Not Know" [hereafter cited as "Propellant Rocketry"], AIAA Paper 99-2925, Jun 99, p. 3; "Solid Rocket," pp. 1055-1056, 1058; "My Memoirs," pp. 3-5.

Minuteman and its successors showed the advantages of solid rockets and paved the way for their widespread application. Aside from contributing to the technological base on which the Minuteman and its propellants were designed, especially larger engines, the Rocket Propulsion Lab had a very direct role in validating the missile. A group of its engineers under John Marshall proposed to Ed Hall, who was then the director of Minuteman, that it was theoretically possible to launch a solid rocket directly out of a silo. Previous missiles were either raised out of the ground on elevators prior to launch or were ejected by compressed air before firing. Temperature and stress studies confirmed the theory and Hall approved it for the program, taking the final conceptual step in making the Minuteman a durable, reliable, and responsive deterrent. The Rocket Lab participated heavily in the test phase of Minuteman. Scale tests of the missile and its motors, including silo firings, occurred by 1959. The Lab built a full-scale silo launch facility, which experienced the first ever silo launch of a missile on 15 September 1959. These tests confirmed not only the viability of the rocket, but validated the size of the silo.[7]

The Rocket Propulsion Lab's Dr. Robert Corley, later its chief scientist, is credited with leading the development of the most widely used solid propellant binder, hydroxyl-terminated polybutadiene (HTPB). The low viscosity of HTPB permitted mixing of propellants with higher solid loadings which provides higher density and performance. The superior microstructure of HTPB provides outstanding propellant mechanical properties which meet the stringent motor structural requirements. Bonding agents provide the critical adhesion between the polymer (HTPB) and solids (fuels and oxidizers) that comprise a solid propellant. This bonding between the polymer and the solids is what provides the superior mechanical properties. Sinclair Oil originally patented the principal HTPB (R45-M) version in 1961 as a commercial adhesive and sealant and it was

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[7] *Ace in the Hole*, pp. 79-86, 148-151; Website, Edwards history office, "Air Force Flight Test Center Moments in History: The Ace in the Hole," available on the internet: http://www.edwards.af.mil/moments/docs_html/59-02-17.html, as of 17 Nov 05.

produced by ARCO Chemical. Its commercial origins made HTPB relatively inexpensive. R-45M offered excellent mechanical and processing properties, leading Dr. Corley to focus the propulsion industry's research on that variant. Its demonstrated qualities led to a series of development programs, not only in the Air Force, but also in the Army and Navy. The first missile system to use HTPB was the Reduced Smoke Maverick Missile, again led by Dr. Corley. By the 1970s, HTPB was in service and is now used in 90 percent of the world's solid rockets.[8]

The Rocket Propulsion Lab made many other equally critical contributions to the development of modern solid rocket motors, both large and small. The test stands on Leuhman ridge have supported every solid ICBM program from Minuteman, through the Titan series, to the Peacekeeper and Small ICBM of the 1980s. One of the first programs undertaken by the lab when it was consolidated at Edwards in 1959 was the Ballistic Test and Evaluation System (BATES) solid rocket motors. A lab team led by Wilbur Andrepont recognized the need for a high-precision testing capability to assess vendor propellant performance and a sub-scale method of predicting performance of larger motors. They designed in-house a series of BATES motors that "became the universally accepted basis for performance measurement" and have been fired more than 4,000 times over the next forty years. The Lab's scientists and engineers made major contributions to the field in non-destructive testing and evaluation techniques, stress and failure analysis, fracture mechanics, propellant aging, and propellant formulation. Other seminal developments achieved or sponsored by the Rocket Propulsion Lab included: composite cases, strip laminate metal cases, extendible exit cones, thrust vector control systems, non-asbestos insulations, wound-on insulation,

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[8]   E-mail w/attachment, Robert Corley, AFRL/PRS, and Kevin M. Rusnak, AFRL/HO, "RE: Solid Rocket History Question," 18 Nov 05; "My Memoirs," pp. 4-5; "Solid Propellants," pp. 1114-1115. Note that Davenas suggests Aerojet was experimenting with HTPB during this same time period; "Propellant Rocketry," pp. 7-9.

laser fiber optic ordinance, and smokeless propellants. The science relevant to solid rockets benefited greatly from the contributions of the Rocket Propulsion Lab in areas such as combustion, performance prediction, plume phenomenology, and motor hazard evaluation. When the impending end of the Cold War resulted in a sharp decline in solid rocket development funding, the lab led the institution of the current Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program that continues the improvements started decades earlier.[9]

Solid rocket motors are part of nearly every rocket system in use today, including commercial, military, and civilian space launch, orbit transfer, strategic missiles, and tactical missiles. Though solid rockets have been around for centuries, it was only in the last fifty years that they took their modern form – reliable, storable, and scalable. Engineers and scientists from what became the AFRL Propulsion Directorate at Edwards AFB were at the forefront of the community that brought these devices from the realm of the ineffective and impractical to the indispensable.

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[9]   "Solid Rocket," pp. 1046, 1053; Paper, R. Geisler and C. Beckman, "The History of the BATES Motors at the Air Force Rocket Propulsion Laboratory," AIAA Paper 98-3981, Jul 98; "My Memoirs," pp. 4-7; Corley e-mail to Rusnak.

Modular Airborne Fire Fighting System (MAFFS)

A series of raging brush and forest fires in 1970-71 set off a chain of events in the upper echelons of government that led to the development and use of a new fire fighting system known as the Modular Airborne Fire Fighting System or MAFFS. Fires in remote and inaccessible areas, such as those that threatened Air Force Early Warning Radar stations in Alaska, presented the most serious problems for fire fighting units. Also, Air Force personnel inadvertently ignited fires on bombing ranges, such as in 1971 when practice bombs burned 29,300 acres of a leased range in North Carolina, forcing the Air Force to pay the owners over $500,000 in damages. After experiencing these serious losses, Secretary of the Air Force Robert C. Seamans, Jr., and other top Air Force officials believed a MAFFS-type system offered an ideal solution to combat these fires.[1]

Fires on military property represented only one aspect of the overall fire fighting problem. In 1970 privately owned aerial tankers and conventional fire fighting teams failed to contain a series of devastating brush and grass fires in Southern California. Every year forest fires nationwide burned roughly 5,000,000 acres, causing an average of 25 deaths and 1,350 injuries, and annual property damages and losses estimated at $300 to $600 million. These statistics prompted several of California's congressmen to request the Department of

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[1] Monograph, Robert W. Duffner, "MAFFS, Modular Airborne Fire Fighting System" [hereafter cited as "MAFFS"], Sept 1979, p. 1; Interview, Dr. Robert W. Duffner, AFWL/HO, with Fred H. Peterson, MAFFS Project Officer, 24 May 1979; Interview, Duffner with William L. Lehmann, AFWL/CC, 27 Aug 1979; Rpt, Atlee H. Bussey and John J. Harrington, FMC, "Modular Airborne Fire Fighting System," Nov 1973; Research paper, Lt. Col. William D. Anderson, Air War College, "Forest Fire Suppression: Should the Air Force Help?" April 1972, pp. 38-39.

Defense develop equipment to fit existing military aircraft to help combat large grass, brush, and forest fires.[2]

These efforts, with encouragement from the Department of Agriculture and its U.S. Forest Service (USFS), produced significant results. During informal discussions in January and February 1971, the Air Force and the Forest Service described a MAFFS system married with military cargo aircraft that would be mutually beneficial. The Forest Service would purchase the system and pay the Air Force to fly MAFFS on their aircraft to fight fires on non-Air Force property, while the Air Force would lease it when fighting fires on Air Force property. The Secretary of the Air Force directed the Chief of Staff in February 1971 to design and develop a fire fighting system that could be palletized and loaded and unloaded aboard Air Force aircraft so as not to impair military logistics capabilities. The Deputy for Laboratories in the Office of the Assistant Secretary of the Air Force, appointed to coordinate the program with other government agencies, contacted the commander of the Air Force Weapons Laboratory (AFWL) to have the lab's Civil Engineering Research Division turn the concept into reality. About the same time, Food Machinery Corporation (FMC) submitted an unsolicited proposal for the Modular Airborne Fire Fighting System to the Air Force. The desire was to have an operational system ready for the next fire season in the summer and fall of 1971.[3]

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[2]   "MAFFS," pp. 1-2; Rpt, Atlee H. Bussey and John J. Harrington, FMC, "Modular Airborne Fire Fighting System (MAFFS)" [hereafter cited as "Modular Airborne"], AFWL-TR-73-271, June 1975, pp. 1-7; Research paper, Maj John A. Watring, Air War College, "An Investigation of the Feasibility of the USAF Supporting National and State Forest Services in Combating Forest Fires," May 1973, pp. 1-3.

[3]   "MAFFS," pp. 2-3; Interview with Lehmann, 27 Aug 1979; Ltr, Robert C. Seamans, Jr., Secretary of the Air Force, to Clifford M. Hardin, Secretary of Agriculture, "subj: Assistance with Forest Fires," 26 Feb 1971; Memo, Robert C. Seamans to CS, "subj: Air Force Fire Fighting Capabilities," 26 Feb 1971.

In mid-March 1971, AFWL established a sole source procurement action with FMC based on FMC's unsolicited proposal. AFWL cited the urgent need to field an operational system and FMC's extensive experience in developing large capacity airborne spray systems. A pre-contract cost letter authorized FMC to begin development. Thus, AFWL cut through much of the bureaucratic red tape, and FMC began work on MAFFS by 1 May 1971.[4]

In late March, a MAFFS planning and coordinating meeting established lines of responsibility among the parties that included the Air Force, AFWL, the Forest Service, and Food Machinery Corporation. At this meeting, Air National Guard representatives advised using the C-130 aircraft for the test bed. Additionally, AFWL arranged for support from other Air Force organizations, including the Air National Guard, who would supply the aircraft and crews needed for the tests.[5]

The emphasis of this new system was on improving the state of the art rather than developing a completely new approach to aerial fire fighting. Aircraft had begun delivering fire suppressants as early as 1921, but a 1936-39 experimental program deemed this technique impractical. Practicality arrived in 1953 when a DC-7 carrying water in ballast tanks successfully inaugurated aerial fire fighting. During the 1950s fire retardant chemicals evolved and replaced water as the most effective agent. Private companies bought and converted World War II-vintage aircraft to deliver the retardant. A distinct advantage of the MAFFS design was its ability to discharge retardant using compressed air rather than depending on the gravity system used by commercial tankers. The gravity system generated "globs" of retardant that sometimes damaged equipment or

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[4] "MAFFS," pp. 3-4; Ltr, Lt. Col. Teske, AFWL/DEZ, to DE, "subj: Purchase Request FY7617-71-10244: Modular Airborne Fire Fighting System," 12 March 1971; Ltr, Col Rowden to AFSWC (PMR), "subj: Letter of Urgency," 15 March 1971.

[5] "MAFFS," pp. 4-7; Interview with Peterson, 24 May 1979.

injured personnel on the ground, while compressed air "sprayed" the retardant without those deleterious effects.[6]

Initially, AFWL directed FMC to deliver a two-tank prototype system, each tank with a 500-gallon capacity, within a four month period. Engineers projected the two-tank MAFFS would have roughly twice the fire-fighting capacity of existing air tankers. Over a six week period in May and June 1971, FMC developed the two-tank configuration by modifying existing tank systems to fit the larger C-130 aircraft and to carry more retardant. FMC then began conducting ground tests of MAFFS, first as compressed air pumped water from the two tanks through a manifold system out two 14-inch discharge tubes, then discharging fire retardant off the edge of a cliff to obtain some idea of the drop pattern. The contractor then installed MAFFS aboard a C-130 aircraft and determined that a discharge nozzle parallel to the longitudinal axis of the plane proved superior to one set at a 90-degree angle. The tests demonstrated the feasibility of the MAFFS concept so actual aerial testing of the system could begin.[7]

As a demonstration prototype, rather than a production prototype, the two-tank MAFFS was designed to lay down retardant so that the Forest Service could measure ground pattern and coverage. Aerial testing began at the Air Force Flight Test Center, at Edwards AFB, California. Flight crews conducted ten flight tests. The first two flights discharged colored water at 20 pounds per square inch (psi), and the rest used retardant at 50 psi. The flights also evaluated discharge tubes at various angles. Members of the Forest Service's Forest Fire Research

[6] "MAFFS," p. 8; Statement of Work, n.a., "subj: MAFFS, Contract F29601-71-C-0088," n.d.; Ltr, Merle S. Lowden, Director, Fire Control, U.S. Forest Service, to record, untitled, 29 March 1971; Article, n.a., "C-130 Adapted for Fire Fighting," *Aviation Week & Space Technology*, 12 March 1973.

[7] "MAFFS," p. 9; Taped comments on MAFFS prepared by Arnold A. Adams, Manager, Government Liaison, FMC, 25 May 1979; Rpt, John J. Harrington, FMC, "Contractor and Government Test Plan for MAFFS Test Device" [draft], June 1971.

Laboratory devised and constructed a fire retardant grid collection system, captured, then measured and tested the dispersed liquid in a nearby makeshift lab. Ground dispersion density patterns were mapped to determine ground coverage. The initial response from the USFS was highly positive, although the laydown patterns needed improvement.[8]

The success of the two-tank MAFFS led directly to development of a five-tank prototype. In August, key AFWL and FMC project personnel discussed design modifications needed to expand the system and resolve the laydown problems. Changes included increasing the diameter of the discharge tubes, angling the nozzles inward instead of parallel to the flight path, and increasing their length. To have the five-tank system available for any part of the 1971 fire season required immediate and coordinated action on the part of all participants.[9]

FMC designed and built a five-tank MAFFS ready for testing in approximately five weeks. For the ground testing phase, which started in late September, FMC technicians evaluated the plumbing, pumping water through the system at pressures that competently reached 85 psi, far beyond planned levels. Next, the system was loaded aboard an Air Guard C-130 aircraft to verify physical compatibility, then moved to Edwards AFB and tested in 14 flights. The flights were mostly at altitudes of 150 feet, which the USFS considered the optimum height to drop retardant, at 130 knots speed, dropping retardant at the rate of 400 gallons per second over an expanded test grid.[10]

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[8]   "MAFFS," pp. 9-15; Taped comments, Adams, 25 May 1979; "Modular Airborne," pp. 1-7; Article, n.a., "Fire Fighting from Air Proves Feasible," in KAFB *Focus*, 13 Aug 1971.

[9]   "MAFFS," p.16; Interview with Peterson, 24 May 1979; Rpt, Charles W. George, Northern Fire Fighting Laboratory, "Report on Tests of FMC MAFFS," Oct 1971.

[10]   "MAFFS," pp. 16-17; Taped comments, Adams, 25 May 1979; Interview with Peterson, 24 May 1979.

The opportunity to use MAFFS on an actual fire came on 8 October 1971 when the Secretary of the Air Force directed the Air Guard to assist the Forest Service in fighting a fire in California's Los Padres National Forest. The MAFFS C-130 aircraft and crew flew seven missions. MAFFS hardware performed satisfactorily in terms of releasing fire retardant. Unforeseen conditions, including poor air-to-ground communications and the difficulty in maneuvering the C-130 aircraft over steep and rugged terrain, resulted in reduced efficiency. In spite of these problems, the Forest Service rated the C-130 drop patterns as "adequate," recognized the system's use for releasing retardant in long swaths, and suggested that the USFS train Air Force crews in aerial fire fighting tactics.[11]

Based on the performance records of the initial two- and five-tank systems, AFWL laid out the groundwork for design and development of a five-tank MAFFS operational prototype. Government and industry met in November 1971 and May 1972 to ensure that MAFFS was designed and constructed to be compatible with the C-130 aircraft. Changes incorporated into the new design directly evolved from lessons learned. The most significant alteration involved relocating the discharge tubes from the side doors of the aircraft, where they were non-retractable and thus limited cruising speed, to the rear cargo ramp where they could be retracted. Other design considerations included palletizing the MAFFS so that it could be quickly loaded and off-loaded using a standard Air Force cargo-handling system, increasing the diameter of the discharge tubes, and minimizing the tank module weight by using aluminum instead of steel. The contract with FMC was signed in June 1972.[12]

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[11] "MAFFS," p. 20; Rpt, Herbert J. Shields, San Dimas EDC, "C-130 MAFFS Use on Romero Fire, October 8-10, 1971," n.d.

[12] "MAFFS," pp. 22-24; Memo for record, Fred H. Peterson, "subj: MAFFS," Feb 1972; Memo, to DEZ, et al., Peterson, "subj: MAFFS," 24 Feb 1972; Message, AFWL to TAWZ, Col. Rowden, "subj: MAFFS," 14 March 1972; Message, AFSC to CSAF, "subj: MAFFS," 11 March 1972.

By December 1972 the finished five-tank production model was ready for final testing. Contractor ground test results verified the reliability of the system. Air Force crews then conducted the operational test and evaluation of the MAFFS. Ground crews evaluated the speed of loading and off-loading the system. Non-drop flights evaluated the performance capability of MAFFS, and then a crew flew 24 sorties on the C-130, dropping retardant and water at a USFS site. The aerial tests found that a parabolic nozzle laid down a longer and more uniform pattern than a straight nozzle, and the best position for the two discharge tubes was alongside the plane with the tubes extended to 18 inches below the ramp door. These test results showed that MAFFS outperformed any of the available aerial-delivery systems in terms of length and concentration of retardant on the ground. This performance level far exceeded that of smaller-tank capacity aircraft that had to make multiple drops to attain the same coverage provided by MAFFS, cutting into the critical element of time.[13]

After the contractor made adjustments to the system, final flight tests began in July 1973. A MAFFS-equipped C-130 followed a Forest Service lead aircraft, simulated actual air attack, communications, and procedures. USFS personnel declared the ground patterns were good. Then starting in August, MAFFS crews dropped retardant on four fires burning in national forests in Montana and California. Forest Service personnel stated that the tests and evaluations demonstrated the MAFFS to be "an effective fire suppression tool."[14]

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[13] "MAFFS," pp. 26-27; Interview with Peterson, 24 May 1979; "Modular Airborne," pp. 5-6, 28-42; Rpt, Charles W. George, "Preliminary Conclusions—FMS—MAFFS Pattern Evaluation," 15 Feb 1973; Article, n.a., "Air Force/Forest Service Join in Fire-Fighting Test," in *Armed Forces Journal,* April 1973, p. 19.

[14] "MAFFS," pp. 36-37; "Modular Airborne," pp. 51-52; Ltr, Boise Interagency Fire Center, to R.L. Bjornsen, Assistant Director, Fire Management, "subj: Module Airborne Fire Fighting System Phase II and III Report, prepared by Norman C. Anderson, PLO," 8 Jan 1974, with attached report.

After two and a half years of designing, building, and testing at a total cost of $470,942, AFWL determined that MAFFS-equipped military cargo aircraft could be used to disperse fire retardant, and could effectively assist the USFS in controlling fires. MAFFS offered a number of advantages. First, it was compatible with military C-130 aircraft equipped with a standard cargo-handling system and could be installed without any modifications. Second, the system could be loaded and readied in less than two hours and be removed in less than 20 minutes. Third, MAFFS was compatible with existing Forest Service ground facilities, could be filled with retardant and compressed air in less than 10 minutes, and the system's operator could pre-select discharge pressures to achieve a desired discharge rate and density. Lastly, MAFFS retardant ground patterns were effective at altitudes between 150 and 1000 feet above the terrain, even in cross winds of up to 24-30 knots, and no aircraft control problems occurred during discharge.[15]

The value of this system was immediately acknowledged by the R&D community. In September 1972, Industrial Research Magazine presented the Air Force Weapons Laboratory and Food Machinery Corporation's Defense Technology Laboratories with its coveted I-R 100 award, citing MAFFS as one of the 100 most significant new technical products for the year 1972.[16]

The initial implementation of MAFFS proved problematic, but in the long run, this innovative system has become a valued contribution to fire fighting technology. Throughout the developmental process, private air tanker

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[15] "MAFFS," pp. 38-40; R&D Case File Comp Report, n.a., Project ILIR 71-08, "Modular Airborne Fire Fighting System," 13 Feb 1978; R&D Case File Comp Report,, Project 2102 2F 04, "Modular Airborne Fire Fighting System, MAFFS," 13 Feb 1978.

[16] "MAFFS," pp. 40-41; Ltr, Niel P. Ruzic, President, Industrial Research Incorporated, to A.H. Bussey, Program Manager, FMC, "subj: Tenth Annual I-R 100 Conference and Awards," 3 July 1972.

companies that contracted with the Forest Service complained that MAFFS and its use by the Air Force would take away their livelihood. The private tanker operators concluded a memorandum of understanding with the government that stated all available contractor aircraft had to be in use before the MAFFS could be brought on a fire scene. In 1974, the Forest Service purchased seven MAFFS systems and stored them at Air National Guard and Air Force Reserve bases across the nation. Between then and mid-1979, the Air Force MAFFS program was used only eight times (not counting its use during the testing phase) at fires on National Forest land in California and New Mexico. To date, the Air Force continues to utilize MAFFS when called upon to contain or counter forest fires on its own or other government property. During and after 2002, the Forest Service and Bureau of Land Management grounded much of the aging commercial tanker fleet following two fatal in-flight catastrophes. The Air Force MAFFS units, whose crews had accumulated valuable experience in the previous years, have met the challenge that this void created. Additionally, under an agreement with the U.S. State Department, foreign governments can request Air Force fire fighting assistance. In 1997, Air National Guard MAFFS units flew 250 sorties to assist Indonesia in suppressing massive man-made wildfires whose smoke threatened to create an environmental disaster.[17]

The success of MAFFS, and its aging thirty-year old equipment, has spawned a next generation system, MAFFS 2. This new USFS system may make substantial improvements, including reducing tank weight again by using composite materials, employing a positive-feed delivery system, increasing the total volume of retardant to 3,600 – 4,300 gallons (depending on the C-130

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[17] "MAFFS," pp. 41-45; Telecon, Duffner with Norman C. Anderson, "subj: Deployment of MAFFS," 22 June 1979; Memo of Understanding, between Department of Defense and Departments of Agriculture and Interior, signed by Howard H. Calloway (25 April 1975), Earl L. Butz (10 January 1975), and Stancly K. Hathaway (26 June 1965); Article, n.a., "Fire Fight," *Airman,* Dec 1977, pp. 24-30; Web article, 1st Lt. Teresa Howes, "Wyoming Fights Blazes in Indonesia," at http://www.forum.apan-info.net/Summer_98/FIRES_r.html as of 26 July 2005.

version flown), and saving time and money by replacing ground support equipment with a self-contained on-board compressor system. The highly successful Modular Airborne Fire Fighting System is an example of the best work the lab and their contractors can achieve when called upon to find a quick response solution to a potentially life-threatening situation.[18]

[18] Web article, n.a., "Military Airborne Firefighting System 2nd Generation (MAFFS 2)," at http://www.fs.fed.us/fire/aviation/fixed_wing/maffs_II/index.html, as of 26 July 2005.

More Electric Aircraft (MEA)

Electrical power systems have been part of aircraft since the first powered flights. The earliest applications were solely for the provision of spark for the piston engine ignition systems, which were powered by magnetos initially, but later supplanted by batteries. As the operating environment of aircraft expanded, so did the power requirements. Useful and practical flight for the military involved flying in bad weather or under low-visibility conditions, creating a potentially hazardous situation in very simply equipped aircraft. This concern resulted in battery-driven aircraft landing lights constituting the first use of onboard electrical power, other than for the engine. This innovation occurred at the Army Air Service's (later Air Corps) laboratories at McCook Field in Dayton, Ohio. That organization, later moved to Wright Field, split the responsibility for electrical system development and testing between two labs: one became the Power Plant Laboratory that worked on electrical engine ignition, while an electrical laboratory specialized in aircraft and ground lighting systems. It was the need for lighting that foremost drove early development of the electrical systems, including batteries, generators to charge the batteries, a primitive electrical distribution system, and a control system for operating the lights. Later developments of the radio, electrical instrumentation, and navigation devices further pushed the development of more sophistical power systems. The ubiquitous Liberty engine that was produced in the U.S. by the thousands for World War I had a battery-operated ignition with a generator to charge the battery and supply power for accessories. The generator produced 100 amps at 30 volts and took 4 horsepower to drive, which was about 1 percent of the engine's output. The addition of aircraft radios interfered with battery ignitions and forced a return to the use of magnetos.[1]

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[1] Tech rpt, Albert Miscnko, "Aero Propulsion and Power Directorate: The McCook Field Years (1917-1927)," AFRL-PR-WP-TR-1998-2080, Feb 95, pp. 3-4; Book, Samuel D. Heron, *History of the Aircraft Piston Engine* [hereafter cited as *Aircraft Piston*], (Detroit: Ethyl Corp.), 1961, pp. 93-95; Paper, Lowell D. Massie, "A History of the Aerospace Power Division" [hereafter cited as "Aerospace Power"], 1 Scp 92, pp. 1-3.

Following the initial spate of developments, the military found little incentive to continue to invest in major improvements to aircraft power technology. Prior to the Second World War, the Air Corps transitioned many innovations from the private sector, such as more reliable equipment and the electric starter, but it also made its own developments in radio interference shielding and spark plugs. The burgeoning of commercial air travel in the 1930s and concomitant demand for passenger comforts were the most significant forces in ushering in the widespread use (and improvement) of aircraft electricity. Out of that demand came environmental control systems, on-board secondary power generation capabilities, auxiliary power units (APUs), and improved batteries. At the outset of World War II, direct current (DC) systems were the standard for aircraft, but alternating current (AC) moved to the forefront of development work as power demands skyrocketed. The dominant 24-volt DC systems, used in most military aircraft, powered items such as wing flaps, propeller pitch and engine controls, radar, de-icing equipment, navigation equipment, remote-controlled gun turrets, and cabin pressurization.[2]

Some of the aircraft used during World War II were considered "all electric" by the nomenclature of the day. The famous Boeing B-17 Flying Fortress fell into this class, as its six 9-kilowatt generators "provided power for all the usual services [flaps, gear, avionics, etc.] and also for controlling, coordinating and maneuvering five-gun turrets." The term "all electric" was applied to aircraft whose designers chose to maximize the use of electricity when faced with options such as hydraulics or pneumatics. Designed in the mid-1930s, the B-17 came at a point when aircraft size, complexity, and capability met with advancements in hydraulic and electrical technologies such that either system

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[2]   "Aerospace Power," pp. 3-4; *Aircraft Piston,* pp. 93-95; Book, R. H. Kaufmann and H.J. Finison, *D-C Power Systems for Aircraft* (New York: John Wiley & Sons, Ltd.), 1952, pp. 1-2.

offered the means to more effectively operate many of the vehicle's systems. Some, like a radio, obviously required electrical power, while others required greater motive force than flight weight/size electric motors could provide. Aircraft flight control surfaces (ailerons, rudder, and elevators) fell in the middle of this spectrum. The size and speed of some modern military aircraft made it physically impossible for pilots to control their aircraft using the traditional method of muscles pulling on sticks and rudders, connected by long cables to the aerodynamic surfaces. It became evident that some method of boosting human power through artificial means was critical. At the war's outset, the Army Air Corps commissioned designs for a long range, very heavy bomber to supplant the B-17, to which Boeing, Douglas, and Lockheed responded. In support of Lockheed's entry, the XB-30, the company conducted an engineering trade study to compare the implementation of electrical power drives and hydraulics, including their use in flight controls. The conclusion drawn suggested there was inadequate electrical generating capacity and that the weight and volume of power conditioning was prohibitive for that application. For the next fifty years, hydraulic-powered flight controls were standard equipment for all but the lightest aircraft.[3]

Aircraft developed over the course of the Cold War evolved with "a complex, heavy, high maintenance hybrid of mechanical, hydraulic, pneumatic, and electrical subsystems." The electrical systems progressed at a rapid pace following World War II. In 1946, the massive B-36 bomber became the first military aircraft to use AC power and when the B-52 emerged a decade later, it

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[3] Book, Lewis F. Wainwright, *Aircraft Electrical Practice* (London: Odhams Press Ltd.), 1961, pp. 7-10; Book, Jacob Vander Muelen, *Building the B-29* (Washington, D.C.), 1995, ch. 1; Book Randolph Matson, *Aircraft Electrical Engineering* (New York: McGraw-Hill Book Company, Inc.), 1943, pp. 174-181; Brfg, James S. Cloyd, AFRL/PROP, "Power Thrust Historical Perspective" [hereafter cited as "Power Thrust"], 19 Nov 04; Article, James S. Cloyd, "Status of the United States Air Force's More Electric Aircraft Initiative," *IEEE AES Systems Magazine,* Apr 98, pp. 17-18; Article, Michael Kelly, "'More electric aircraft' – an old concept with new life," *Leading Edge*, Jan 03, p. 23.

had a 150 KVA total electrical capacity. The post-Sputnik revolution affected nearly every aspect of military research and development, including aircraft power. In 1957, the Air Force reorganized several of its laboratories. The former Power Plant Lab and the former Propeller Lab became the Propulsion Lab (re-dubbed the Air Force Aero Propulsion Lab in 1963), which consolidated electrical power personnel from an electrical lab and the Power Plant Lab into a new Aerospace Power Division, now responsible for every aspect of aircraft and spacecraft power systems. Its scientists and engineers were responsible for critical advances, such as the hydrazine-fuelled auxiliary power unit (F-16), titanium hydraulic lines, fire-proof hydraulic fluid and high pressure distribution systems, fuel cells, new types of rechargeable batteries, and the variable-speed, constant-frequency generator developed in the 1970s and applied to the F-117, F-16, and other aircraft of that period.[4]

Despite some dramatic changes in technology between the 1940s and the 1980s, the basic structure of powered aircraft flight controls remained essentially unchanged and hydraulically-driven. As late as 1984, the lab unsuccessfully looked at replacing some of the hydraulic and mechanical subsystems with electricity. A new, 85 horsepower electric fuel pump devised by the Aero Propulsion Lab was one such foray, but the size and weight of associated power conditioning continued to render application to flight controls and engine ancillaries infeasible. It took a concerted effort in other areas to advance electrical technology enough to change that long-standing obstacle. Starting in 1969, the Aerospace Power Division participated in the Airborne Laser Laboratory (ALL) effort to put a weapon-style laser aboard a large aircraft. The power engineers recognized that the ALL team had insufficiently studied the

[4]   "Power Thrust;" "Aerospace Power," pp. 5-7; Manuscript, Dr. James F. Aldridge, ASC/HO, "USAF Research and Development," 1997, pp. 47-48; Paper, Albert E. Misenko and Gary D. Streby, "Seventy-Five Year History of the Air Force Aero Propulsion and Power Directorate," Oct 94, pp. 126, 141, 148-150; Paper, Joseph Weimer, AFRL/PRPE, "Past, Present, and Future of Aircraft Electrical Power Systems," AIAA Paper 2001-1147, Jan 01, pp. 2-4.

power requirements of their laser, so they stepped in to develop and test technologies such as superconducting wire, compact generators, helium-cooled magnets, magnetohydrodynamic generators, high energy storage capacitors, and superconducting alternators and generators. The ALL failed as a weapon, but this technology base proved critical after President Ronald Reagan announced the start of the Strategic Defense Initiative (SDI, or "Star Wars") in 1984. This planned missile defense program was extraordinarily ambitious and came with a large pool of funding for supporting technologies. The Aerospace Power Division applied their efforts to developing revolutionary new power controlling electronics, including the Metal Oxide Semiconductor-Controlled Thyristor (MCT) silicon-based power switch, that significantly reduced the size of power conditioning components while improving their reliability. That work resulted in the first flight-weight electrical components of sufficient power to perform aircraft functions previously outside that realm of capability.[5]

Unfortunately, the SDI power work at Wright-Patterson came to an abrupt end in 1990 when the Air Force consolidated its laboratories into four "super labs." The responsibility for space power went to the new Phillips Laboratory, headquartered at Kirtland Air Force Base. That transfer left the Aerospace Power Division without its major program, so its scientists and engineers turned their expertise in power technology, including components, capacitors, thermal management, and generators, to aircraft. They studied all the mechanical, hydraulic, and pneumatic systems that could be replaced by electrical components. Their studies showed a "more electric aircraft" (MEA) that replaced these other subsystems could provide increased reliability and survivability, while reducing the life cycle cost and logistical footprint. As a result, the Propulsion Lab (PR) created its three-phase More Electric Aircraft Initiative in 1993. By

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[5]   "Power Thrust;" "Aerospace Power," pp. 10-14; Telephone interview, Dr. Robert H. Heiser, with Kevin M. Rusnak, AFRL/HO, 30 Aug 05; "Status of the United States Air Force's More Electric Aircraft Initiative" [hereafter cited as "More Electric Aircraft"], pp. 17-18.

1995, the MEA expanded into the More Electric Initiative (MEI), as the technologies had widespread application to naval vessels, army ground vehicles, and helicopters. It was eventually endorsed by the SAB's *New World Vistas* study and the Joint Aeronautical Commanders Group and adopted by the Air Force as a high visibility research-based initiative. Development and risk-reduction programs included the "Electric Starlifter" C-141 from 1996-1998, the Power Management and Distribution System for an MEA (MADMEL), and the Joint Strike Fighter (JSF) Integrated Subsystems Technology (J/IST) effort from 1997-2001. All these programs sought to gradually integrate "more electric" components, such as fuel pumps, an external integral starter-generator, and a 270 VDC power system (as on the F-22). The plan for the future considered the total replacement of mechanical and pneumatic systems with electric components and the integration of a starter-generator into the turbine engine core. The elimination of hydraulics, which were considered vulnerable, flammable, and leaky, with electrical power was high on MEA's agenda. Those systems served primarily the flight controls and landing gear. "Power by wire," a concept originally considered for the space shuttle twenty years earlier, came to fruition when Lockheed's X-35, with an all-electric flight control system, won the JSF competition. MEA components and systems have transitioned to other aircraft, such as the F-22, B-2, commercial Boeing 787 airliner, and UAV efforts. An ancillary benefit of MEA was the surplus power available after start-up and takeoff, the point at which maximum power was required. The Power Division recognized that the additional generating capacity once in flight could be employed for other uses, including to power some type of directed energy weapon. The Air Force Research Laboratory's Propulsion Directorate continues to pursue technologies relevant to the MEA, from individual electrical components to the crucial subsystems that enable its implementation.[6]

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[6]   "More Electric Aircraft," p. 18; "Aerospace Power," pp. 13-14; History, AFRL/HO, "History of the Air Force Research Laboratory, 1 October 1997-30 September 1998," Vol. 1, Apr 00, pp. 246-253. History, AFRL/HO, "History of the Air Force Research Laboratory, 1 October 2000-30 September 2001,"vol. I, Apr 02, pp. 427-430. Paper,

Joseph Weimer, AFRL/PRPE, "Power Electronics in the More Electric Aircraft," AIAA Paper 2002-0727, Jan 02, pp. 1-2, 5-7; Article, Michael Kelly, "Power Technologies create revolution," *Leading Edge,* Jan 03, pp. 22-23.

Multijunction Solar Cell Technology

Increasingly complex and diversified spacecraft operations demand a commensurate increase in spacecraft power capabilities. New electronic components such as spaceborne computer processors, sensors and optics require more power—for example, communications satellites have doubled their power needs every five years. And with satellites remaining on station for ten years or longer, the longevity, durability, and reliability of spacecraft power systems create additional requirements. Space systems scientists need to generate more power, ensure autonomous and maintenance-free operations, and reduce power system weight and size. Air Force laboratory scientists have made significant contributions to the area of solar cell technology, notably the development of multijunction solar cells. These cells substantially increase power efficiency and have been transitioned to military, government, and commercial spacecraft.

Solar cells, converting the sun's energy into electrical energy, have been the power generation system of choice for space systems. Solar cells require no moving parts and no additional fuel to generate clean, quiet electricity. Indeed, powering satellites constituted the earliest pragmatic applications for solar cells, which began in the 1960s. As semiconductor devices, photovoltaic solar cells initially consisted of thin pure silicon wafers. Producing the cells meant growing and hand-working a single silicon crystal. However, solar cells are inefficient and increasing solar cell efficiency—the ratio of electrical output to solar energy absorbed—has been the central goal for this area of expertise. Higher efficiency translates into significant payoffs. As payloads get heavier, if a smaller solar array can be produced and still yield adequate or greater power, the lighter solar array could allow more missions and equipment to be carried on the satellite.[1]

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[1] Book, Thomas D. Damon, *Introduction to Space: The Science of Spaceflight* (Malabar, Florida: Krieger Publishing Company), 1995, pp. 76-78; History, PL/HO, "Close-out History of the Phillips Laboratory, 1 October 1996 – 30 October 1997"

Solar arrays are constructed by adhering a thin coverglass with attached electrical contacts onto each 20cm^2 solar cell. This configuration, called a Cell-Interconnect-Coverglass assembly or CIC, generates roughly one watt per cell. Satellite solar arrays typically generate from one to fifteen kilowatts and require thousands of solar cells. These cells, mounted onto rigid aluminum honeycomb panels to protect them from breakage, allow the array to be easily pointed at the sun. Hand welding the cells in an electrical series in parallel produces the desired voltage and current for each spacecraft. Typically, solar arrays account for about 10% of a spacecraft's total mass and cost. Because a solar array consists of rigid panels, coverglass, and wiring in addition to the cells themselves, a reduction in solar array area combined with a relatively small increase in solar efficiency results in a significant reduction in solar array mass and stowed volume, the volume occupied when arrays are stowed during launch.[2]

Air Force research into solar cell power systems originally started in the 1950s with the antecedents of the Air Force Aero-Propulsion Laboratory (AFAPL) at Wright-Patterson AFB, Ohio. By the 1970s, the efficiency of silicon solar cells reached about 14%. Researchers sought an increase in efficiency with familiar semiconductor materials so that the aerospace industry might be more accepting of the untried nature of these materials. From 1983 through about 1987, researchers at the Aero-Propulsion Lab (APL) – the direct descendent of AFAPL -- developed an early version of gallium-arsenide (GaAs) cells, which had an average of about 18% conversion efficiency.[3]

[hereafter cited as "Close-out"], vol. I, 1998, pp.754-755; Notes/comments, Donna C. Senft, AFRL/VSSV, "on Multijunction Solar Cell Technology draft," 28 July 2005.

[2] Senft, notes/comments, 28 July 2005; Notes/comments, John M. Merrill, AFRL/VSSV, "on Multijunction Solar Cell Technology draft," 22 Nov 2005.

[3] "Close-out," pp. 755-756; Senft, notes/comments, 28 July 2005.

In addition to higher efficiency, GaAs solar cells have the advantage that they are much more resistant to the damaging effects of solar radiation than silicon cells. This degradation of the cells must be taken into account since solar cells are sized to provide the necessary power levels for spacecraft operations to last until the end of the satellite's lifespan. Increasing cell radiation resistance results in smaller arrays. And unlike silicon, GaAs is a member of a family of semiconductors and semiconductor compounds that can be grown one on top of the other in thin layers. Because of the nearly identical interatomic spacing, this family of materials is compatible for inter-layered growth.[4]

Highly efficient multijunction solar cells are fabricated by choosing semiconductor materials that absorb different portions of the solar spectrum—absorption being determined by the electronic bandgap of the material—and growing thin films of these materials in a stacked configuration. Each layer in the stack absorbs a different portion of the solar light spectrum from ultraviolet to visible to infrared, converting more of the sun's energy to electrical energy than with single junction solar cells. The Air Force's Manufacturing Technology or ManTech program supported production of the GaAs solar cell, and flew the solar panels aboard the Clementine I and STRV-1B satellites.[5]

From 1988 through 1991, the lab worked to develop two-junction Gallium-arsenide/Germanium (GaAs/Ge) based 21-23% efficient solar cells. At that time, four candidate concepts competed in the drive for greater multijunction solar cell efficiency. By 1991-1992, when the solar cell development program transferred

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[4]   Senft, notes/comments, 28 July 2005; Article, Dr. John Brownlee, AFRL/VS, "Dr. Kitt Reinhardt discusses his research with multijunction space solar cells" [hereafter cited at "Kitt Reinhardt"], *Air Force Research Laboratory Technology Horizons*, Dec 2002, p. 10.

[5]   Senft, notes/comments, 28 July 2005; Article, n.a., "Space Technology Research Vehicle Solar Cell Experiment," *Phillips Laboratory Success Stories, 1993-1994*, p. 117; "Kitt Reinhardt," p. 10.

from APL's descendent – the Aero-Propulsion and Power Directorate – located in the relatively newly created Wright Laboratory to Phillips Laboratory's Space and Missile Technology Directorate, only one concept remained. The triple junction solar cell, the only application that appeared ready to go straight to market, had survived. This version of the multijunction solar cell consisted of three layers arranged in order from largest bandgap to smallest, with the thin-films of these materials grown on single crystal germanium wafers. The top cell, made of gallium indium phosphide (GaInP$_2$) converted the 400-650 wavelength band; the middle cell of gallium arsenide (GaAs) converted the wavelength range from 650 to 900; and the bottom cell of germanium (Ge) converted in the wavelength range from 900 to almost 1500.[6]

In September 1995, a joint Wright Laboratory/Phillips Laboratory/NASA Lewis Multijunction Solar Cell ManTech program began to maximize triple solar cell performance and scale them up to production size, quantity, and yield. The goals of this ManTech-funded program were to increase manufacturer's lot average cell efficiency and limit production costs. To do this, ManTech laid out a two-phase program: first, under the baseline definition phase, attain a minimum 24% average efficiency, and second, under the optimization and validation phase, focus on optimizing the means for manufacturing production-sized runs of these cells. Improving consistency in manufacturing processes would help improve the yield of production runs. When the number of good cells produced by each run increased, the overall cost to the Air Force decreased. By ensuring mass production by more than one vendor, competition could help keep supplies up and prices down. Hence, the Air Force invested in the ManTech program to enhance its ability to meet its mission in space.[7]

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[6] "Close-out," pp. 755-756; Article, n.a., "High Efficiency Solar Cell Program," *Phillips Laboratory Success Stories 1993-1994*, p. 87; Senft, notes/comments, 28 July 2005; Merrill, notes/comments, 22 Nov 2005; "Kitt Reinhardt," p. 10.

[7] "Close-out," pp. 756-758; Article, n.a., "Multijunction Solar Cell Manufacturing Technology Leads to More Efficient Solar Cells," *Phillips Laboratory Success Stories,*

During the ManTech phase one, two experienced solar cell manufacturers—Spectrolab and TECSTAR—worked with the government team to optimize multijunction solar cell performance. Both contractors, already producing good efficiency dual and triple junction cells, pursued more than one multijunction solar cell design because of the uncertainty of whether or not dual or triple junction cells would be best for phase two production. Dual junction and triple junction cells used an identical basic approach, using $GaInP_2/GaAs$ structures on an inactive germanium (Ge) substrate. Using an active substrate, though, altered the approach used by each contractor for the formation of triple junction cells. Although both worked with active Ge, Spectrolab produced a triple junction cell while TECSTAR created a dual junction-plus device. At the end of phase one in December of 1996, testing of each vendor's cells in a near-space environment took place aboard the specially modified NASA Lewis Learjet. Test results compared very favorably with both products. Notably, growing near-perfect single crystal solar cells optimized efficiency, since defects in the crystals reduced a cell's overall current.[8]

Following these tests, ManTech phase two began in May 1997, with the goal of reducing production costs while maintaining high efficiency. In part, this process meant increasing the individual multijunction solar cell size so as to decrease the overall solar panel size and thus decreasing the pre-deployment stowage necessary. Reductions in cell mass also occurred. By 2000, TECSTAR and Spectrolab had successfully developed triple junction cells having 25% efficiency, while providing 35% more power per cell area over the previous 18% efficient cells, and reducing the cost per watt by 15-20%. Additionally, radiation

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1996, p. 73; Paper, David N. Keener, Dean C. Marvin, David J. Brinker, Henry B. Curtis, and P. Michael Price, "Progress Toward Technology Transition of GaInP2/GaAs/Ge Multijunction Solar Cells" [hereafter cited as "Progress Toward"], Conference Record of the Twenty-Sixth IEEE Photovoltaic Specialists Conference, Anaheim, California, 1997, pp. 787-792.

[8]   "Close-out," pp. 758-763; "Progress Toward," pp. 787-792.

testing of these new types of solar cells, measuring performance degradation induced by ground radiation exposure, provided a comprehensive radiation degradation model. The triple cell multijunction technology quickly transitioned for use by both government and civilian spacecraft.[9]

With the termination of the ManTech program, a new Dual Use Science and Technology (DUS&T) program took its place under the auspices of the Air Force Research Laboratory (AFRL). DUS&T's goal, to achieve 35% efficiency cells, meant developing new materials with more optimal bandgaps and compositional tailoring of the existing material. Initially, the project dealt with the triple cell multijunction solar cells, and increased its conversion efficiency to a record 29%. But TECSTAR decided to pull out of the cell production business in 1999. Fortunately, the startup company EMCORE successfully bid on the DUS&T contract, and within a year provided a competitive product. The appearance of EMCORE re-established the historical dual sources of domestic solar cells, with the associated risk and cost reduction benefits. By early 2002, both Spectrolab and EMCORE offered 27.5% production cells, with best efficiencies in the 29-30% range. In addition to these performance improvements, better production processes have resulted in a reduction of dollars per watt cost for the cells. These solar cell products, by far the best cells in the world, completely dominate the domestic American military, civil, and commercial markets, as well as being selected for many foreign spacecraft. Their rapid insertion into current U.S. military satellite programs attests to their mission-enabling qualities. For example, the Advanced EHF and Wideband Gapfiller spacecraft systems, the follow-on programs to the Military Strategic Tactical and Relay (MILSTAR) program, have been required to transition to the new Evolved Expendable Launch Vehicle class of launchers from the Titan IV launch vehicle used by their predecessor. The high performance solar cells developed by this DUS&T

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[9]   Senft, notes/comments, 28 July 2005; "Kitt Reinhardt," p. 10; Article, AFRL/XPTC, "Tab 2—Emerging Technologies: 25-40% Efficient Multijunction Space Solar Cells," *Air Force Research Laboratory Success Stories, A Review of 2000*, p. 54.

program enabled that transition without a loss in available power that would have otherwise resulted from the necessary decrease in solar array area.[10]

With the significant advances in multijunction solar cell technology, AFRL scientists began to consider the possibilities of four, five, or even six junction cells, with as much as 40% efficiency. AFRL's Dr. Kitt Reinhardt and Sandia National Laboratory's Dr. Hong Hou collaborated on a four-junction gallium indium arsenide nitride (GaInAsN) solar cell, for which they were awarded a patent in 1999. AFRL has contracted with both EMCORE and Spectrolab to produce five or six junction cells, expected to result in 33-35% efficiency. Solar cells with this many junctions are difficult to grow because each junction must produce the same amount of current when exposed to sunlight in order to achieve optimal operation. Also, each of the materials used in the cells must have the necessary bandgap and uniform interatomic spacing. The first six junction solar cells, demonstrated in 2004, produced a voltage twice that of triple junction solar cells.[11]

Expanding on its work in the solar cell sector, AFRL has produced revolutionary research in flexible, thin-film solar arrays. Although thin-film solar cells have a 15% efficiency goal, clearly lower than multijunction solar cells, they make up for that deficiency with lighter weight. The cells, deposited on flexible, thin metal foils or plastic substrates, when incorporated into "blankets" with a lightweight support structure, may result in solar arrays with a power-to-mass ratio three times larger than multijunction solar arrays on rigid panels. Because the thin-film arrays can be compactly rolled or even folded for stowage during

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[10]   Senft, notes/comments, 28 July 2005; "Kitt Reinhardt," p. 10; Article, AFRL/XPTC, "Tab 2—Emerging Technologies, High-Performance Solar Cells," *Air Force Research Laboratory Success Stories, A Review of 2003*, p. 69.

[11]   Senft, notes/comments, 28 July 2005; "Kitt Reinhardt," p. 10.

launch, they will occupy seven times less volume than rigid panel arrays. In addition, by producing thin-film cells in large volume operations designed for the larger terrestrial solar cell market, overall cost may reach one-third the cost per watt for multijunction arrays. Additionally, thin-film solar cells have higher radiation resistance than multijunction solar cells, and the radiation damage that is induced can be annealed from the materials at operational temperatures. Operational flight testing of this new material is expected around 2010.[12]

Scientists from the Air Force Research Laboratory and its predecessors have developed single crystal solar cells with higher efficiencies and lower costs per watt than any previously developed solar cells. The development and introduction of multijunction solar cells over the past decade has enabled significant increases in spacecraft power and a corresponding growth in spacecraft capabilities. Solar arrays comprised of the lab-developed cells have long been incorporated into military and commercial satellites, and are currently baselined on all U.S. military spacecraft now in the acquisition cycle. Attesting to these remarkable advances, the Space Technology Hall of Fame inducted the AFRL Space Vehicles Directorate's multjunction solar cell technology in 2004. Nevertheless, these scientists have not rested on their laurels, but continue to research and develop revolutionary technologies that will benefit spacecraft designers and users for years to come.[13]

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[12]   Senft, notes/comments, 28 July 2005; Paper, Paul E. Hausgen, Jennifer E. Granata, Donna Senft, Pawel Tlomak, and John Merrill, "AFRL Thin Film Solar Cell Development and Upcoming Flight Experiments," AIAA 2004-5734, 2nd International Energy Conversion Engineering Conference, Aug 2004, pp. 1-7.

[13]   Senft, notes/comments, 28 July 2005; Article, n.a., "AFRL Technology Inducted into Hall of Fame," *Air Force Research Laboratory Newsletter*, April 2004.

Nondestructive Inspection and Evaluation

An in-flight failure of an F-111A aircraft in 1969 led to a significant change in U.S. aircraft design philosophy—from "safe life" to "damage tolerance." This event also caused initiation of a major new program in nondestructive inspection and evaluation (NDI/E) at the Air Force Materials Laboratory (ML).

A brief review at this time of preceding, relevant events is instructive. The "cold war" between the United States and the Soviet Union, beginning in the late 1940s, led to efficient airframe requirements with materials pushed closer and closer to their limits. The "safe life" design philosophy evolved following several disastrous airframe failures afterward attributed to metal fatigue. In particular, De Havilland Comet commercial jet transport fuselages exploded in midflight on 10 January and 8 April 1954 because of rapid metal fatigue caused by the stress of cycling a pressurized cabin to high altitudes and back rapidly. Also, the Air Force grounded the entire B-47 jet bomber fleet from April to September 1958 after metal-fatigue cracks resulting from low-level simulated bombing maneuvers were discovered in the aircraft's wings. (In the "Pop-Up" maneuver, for example, pilots flew the B-47 to the target at low-level, then pulled it up to high altitude to release the plane's weapon, and finally dove the aircraft steeply to escape enemy radars.) Aircraft designers began appreciating the necessity of adding the effect of cyclic fatigue loading to the traditional static strength model, and thus they began, as part of the Aircraft Structural Integrity Program, designing aircraft to a target safe fatigue life. The designers adopted a 4x safety factor, which required (in the case of the F-111) conducting rigorous fatigue testing of a full, representative airframe and certain components and subassemblies for 40,000 hours to ensure a safe life of 10,000 hours. The safety factor took into account unknowns, assumptions, and variables applicable to the fleet as a whole.[1]

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[1]   The evolution of the safe-life design philosophy is briefly discussed in Web page, Gerard Redmond, NDTSL-DGTA, RAAF Base Amberley, Queensland, "From 'Safe Life' to Fracture Mechanics – F111 Aircraft Cold Temperature Proof Testing at RAAF

General Dynamics Corporation (Ft. Worth operation of the Convair Aerospace Division) designed the F-111 aircraft as an all-weather multipurpose tactical fighter-bomber. Its unique swing-wing design, in which each wing was attached through a pivot fitting to a central wing carry-through box (WCTB), enabled the aircraft to operate from treetop level to altitudes above 50,000 feet and from slow approach speed to supersonic velocity at sea level and at more than twice the speed of sound at higher altitudes. The aircraft, first flown in 1964, was initially designed for a 4,000-flight-hour safe life, which was the goal of a full-scale fatigue test program begun in August 1968. (Further structural improvements would later increase its design safe service life to 10,000 flight hours.)[2]

Aircraft 67-049 (Tactical Air Command No. 94) was assigned to the 428th Tactical Fighter Squadron, 474th Tactical Fighter Wing, and flown by the highly experienced crew of Maj. Thomas J. Mack and Maj. James L. Anthony. On 22 December 1969 it crashed on the Nellis Air Force Base gunnery range in Nevada after suffering the catastrophic fracture and loss of its left wing during a high-load-factor pull-up from a high-speed, low-altitude, rocket-firing pass, during which the wings were at a 30° angle. Because the aircraft was rapidly rolling out

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Amberly," n.d., available on the Internet at http://www.ndt.net/article/apcndt01/papers/912/912.htm. The B-47 wing cracks are discussed in Web page, GlobalSecurity.org, "B-47 Stratojet United States Nuclear Forces," n.d., available on the Internet at http://www.globalsecurity.org/wmd/systems/b-47-mods.htm.

[2] Report, G. Keith Ritchey, Universal Technology Corp., "F-111 Systems Engineering Case Study," Center for Systems Engineering, Air Force Institute of Technology, n.d., p. 8. The ultimate 10,000-hr design safe service life is cited on an exhibit placard, n.a., "The US Air Force F-111 Fighter Bomber Catastrophic In-Flight Wing Failure Investigation," n.d., on display in a WPAFB Bldg. 653 lobby exhibit as of Oct 05.

of control close to the ground, the crew's attempted ejection was out of escape-module limits, and both crewmen were killed on module ground impact.[3]

Following the accident, the Air Force immediately grounded the entire F-111 fleet of 223 aircraft (the fifth time the aircraft had been taken off flight status since 1966). General Dynamics also halted new deliveries, pending an investigation into the causes and circumstances of the failure, which was carried out by personnel from the contractor, the system program office, the Air Force Plant Representatives office, and the Air Force Materials Laboratory at Wright-Patterson AFB. By mid-January 1970 a preliminary metallurgical review of recovered parts of the aircraft conducted by personnel at General Dynamics determined that the accident had been caused by a manufacturing-introduced sharp-edged forging defect in the lower attachment plate of the triangularly shaped wing pivot fitting about 17 inches from the pivot center line. (This plate and a similar upper plate, both made of D6ac steel, attach the movable wing to the WCTB. At the apex of the triangle each plate has a round hole where it is fitted to the pivot pin.) The General Dynamics conclusion was based on the presence of a decarburized zone at the surface of the flaw and black ferrous oxides at the fracture face, which are characteristic of the high temperatures associated with the forging and heat treatment of the D6ac steel parts of the aircraft. The investigators suggested that the most probable source of the flaw was a cooling crack that occurred after the final forging cycle and that grew during subsequent heat-treating operations. Such a crack would normally be detected and ground out before proceeding with subsequent steps in the fabrication process. Originally 5.72 mm deep, the concave-shaped crack grew by fatigue, during only 104.6 flight hours, an additional 0.44 mm to a critical depth of 6.16 mm. [4]

[3] Web page, F-111.net, "YF-111A/F-111A/RF-111A/GF-111A," available on the Internet at http://www.f-111.net/ as of 12 Oct 05.

[4] Article, n.a., "Budget Constraints, Crash Cloud F-111 Production Program Future," *Aviation Week & Space Technology,* 92, no. 3 (19 Jan 70), p. 19; Conference

Subsequent investigations revealed that the crack was incapable of detection by the longitudinal-wave ultrasonic and magnetic-particle inspection procedures that had been used by the forger (Wyman-Gordon Company of Grafton, Mass.) during manufacturing NDI/E. The sound-wave transmission used during the first of these procedures had been directed almost parallel to the flaw surfaces, and thus the energy return, if any, had been insufficient to detect the flaw. Likewise, the flux fields used in the second of these procedures were inadequate to cause the migration of iron particles to a tight flaw in a part having an unusual shape and large size like the wing pivot fitting.[5]

The investigating team concluded that the flaw was unique and unlikely to occur again (one member estimated that the probability of such a crack developing and escaping detection was one in about 8 million). Nevertheless, because of what Air Force officials considered unwarranted public and congressional pressures that had existed during the F-111 program, they decided that steps needed to be taken to establish more firmly the structural integrity of the F-111 airframe. First, a special ad hoc committee of the Air Force Scientific Advisory Board, chaired by Stanford University professor of aeronautics and astronautics, Holt Ashley, recommended that every F-111 aircraft be subjected to a fracture-mechanics-based low-temperature (-40° F) proof load test (with equivalent loading range of 7.33 g to -2 g) that had been developed and successfully used for pressurized structures in NASA's Apollo manned lunar

presentation, Urban A. Hinders, Aeronautical Systems Division, "F-111 Design Experience—Use of High Strength Steel" [hereafter cited as "F-111"], AIAA Paper No. 70-884 presented at the AIAA 2nd Aircraft Design and Operations Meeting, Los Angeles, Calif., 20-22 Jul 70, pp. 6-8; Article, W. D. Buntin, Convair Aerospace Division, General Dynamics, "Concept and conduct of proof test of F-111 production aircraft" [hereafter cited as "Concept"], *Aeronautical Journal,* 76, no. 742 (Oct 1972), pp. 587-598.

5   Article, n.a., "F-111 Crash Spurs Tightening of Standards," *Aviation Week & Space Technology,* 92, no. 12, 23 Mar 70, pp. 59-61; "F-111," pp. 6-8; "Concept," pp. 587-598.

landing program and in various other missile and space efforts. The major objectives of this proof test program was to (1) screen the structural system for gross defects, including material flaws and any other defect not amenable to standard inspection practices, such as improperly seated bolts and steel parts with improperly heat-treated areas, and (2) provide a basis for establishing inspection intervals for use with the fleet in service. For this program General Dynamics set up four specially built proof-load test cells—two at its Ft. Worth facility; one at the former James Connolly AFB (Waco, Tex.), where it maintained a B-58A inspect-and-repair-as-necessary facility; and one at McClellan AFB near Sacramento, Calif.[6]

As a second step, Secretary of the Air Force Robert Seamens subsequently ordered a significant increase in the service's NDI/E research-and-development level of effort to expedite major improvements in flaw-detection capabilities. Soon thereafter ML initiated a major new program to improve significantly flaw-detection capabilities, improve and/or modify existing NDI/E techniques to improve accuracy, explore and develop new technical approaches and instruments, and establish a strong new NDI/E science base. Among other things, ML personnel improved MPI flux field distributions to detect F-111 target flaws better. They also adapted a new NASA-developed ultrasonic Delta Scan method, which greatly facilitates the detection of a crack oriented vertically to the part surface, to critical F-111 parts. The program pioneered development of a

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[6]   *Ibid.* The Sacramento Cold Proof Test Facility (CPTF) is described at Web page, Greg Hoffman, "F-111 wings: Frozen and Bent," n.d., available on the Internet at http://www.f-111.net/cold.htm on 12 Oct 05. After the USAF stopped operating the F-111, the four original CPTFs were closed, but a new CPTF was built at RAAF Base Amberly to test Australian F-111 aircraft. See Web page, Ben Caddaye, Defence Public Affairs and Corporate Communication, Directorate of Internal Communications, "Frozen Pigs," *Airforce News,* n.d., available on the Internet at http://www.defence.gov.au/news/raafnews/editions/4424/topstories/story07.htm on 12 Oct 05. For an extensive review of the F-111 "Recovery Program," especially the cold proof test concept, see Report, D. M. Forney, Jr., Air Force Materials Laboratory, and H. B. Lowndes, Jr., Air Force Flight Dynamics Laboratory, "Application of F-111 NDI and Cold Proof Test Concepts to Future Weapon Systems," 1 Dec 70.

number of advanced NDI/E systems that later were used in the field. These systems included computerized-axial-tomography (CAT) scan equipment for inspecting the solid-rocket motors of intercontinental ballistic missiles (ICBMs), several approaches to large-area NDI/E of composite airframe structures, and processes and equipment for the automated NDI/E of turbine-engine components in support of the major ML retirement-for-cause (RFC) initiative. A new damage tolerance design philosophy, governed first by "Aircraft Structural Integrity Program" (MIL-STD 1530) and "Airplane Damage Tolerance Requirements" (MIL-A-83444), was in place by 1975. Designers now had to assume that specific "fail-safe" flaw sizes were present in critical components and design accordingly, in the absence of experimentally designed capabilities to detect with NDI/E any smaller sizes, with 90% probability at a confidence limit of 95%.[7]

The Materials Laboratory launched a new long-term advanced development program for NDI/E in 1988. Advocated by the commanders of the Air Force's Systems and Logistics commands, this program, like its predecessor, sought to expedite the development and transition of various NDI/E advances into field applications.[8]

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[7] Report, Donald M. Forney, Universal Technology Corp., "Wing Carry Through Box Failure and Impact on Subsequent Aircraft Development," n.d., pp. 72-81; Report, Donald M. Forney, Universal Technology Corp. (for Nondestructive Evaluation Branch, AFRL), "In Search of Quality: A Historical Review," Oct 05.

[8] This new program was described in conference presentation, Don M. Forney, WRDC/Materials Laboratory, "The Development of Improved NDI/E to Meet Structural Integrity Requirements," WRDC-TR-89-4071, pp. 72-101 in *Proceedings of the 1988 Structural Integrity Program Conference, San Antonio, Texas, 29 November-1 December 1988*, ed. by Thomas D. Cooper and John W. Lincoln, May 1989.

Optical Recording

In some respects, optical recording is as old as the pharaohs, whose hieroglyphs were among the first means by which humans transferred the spoken word into a visual medium by exploiting the variance in reflectivity between papyrus or stone and pigments. (Indeed, this is true of nearly all writing since then with the exception of Braille, developed specifically for the blind.) However, modern optical recording must look, rather to the 19th century invention of photography as perhaps a nearer precursor; for photographs are produced by the action of light on a material medium and then discerned or "read" by how light is reflected from the irregularities in the medium produced when the photograph was "taken." In the end, however, optical recording as it is known today, was made possible only when man was able to control light itself. This was made possible only after the 1960 invention of *light amplification by simulated emission of radiation* or the "laser" for short.[1]

The Air Force Research Laboratory Information Directorate's (AFRL/IF's) predecessor organization, the Rome Air Development Center (RADC), was an early participant in the revolution in optical recording technology. Indeed, RADC had been involved in developing data storage and retrieval technologies from the 1950s. Early projects included adaptation of the French Filmorex Equipment microfilm system (first of its kind in the U.S.) and a system of storing data on one-inch by three-inch magnetic cards.[2]

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[1] See Article, n.a., "Optical Data Storage Systems," n.d., at www.usebyte.com/common/optical_data_storage_systems.htm, as of 31 Oct 05.

[2] Book, Thomas W. Thompson, *The Fifty-Year Role of the United States Air Force in Advancing Information Technology—A History of the Rome, New York, Ground Electronics Laboratory* [hereafter cited as *HRL*], Studies in Twentieth Century American History, vol. 10 (Lewiston, Queenston, Lampeter: The Edwin Mellen Press) n.d., p. 106.

RADC soon moved into examining the methods of computer memory systems. In April 1961, RADC established a data processing facility in its Building 240; one early project was the development of a high-density computer memory with the goal of storing a billion bits of information with an access time of microseconds. In the 1960s, other projects included studying cryogenic random-access memories and methods of extracting data other than over wires. Other efforts included a plated-wire array computer memory and a 100 million bit digital computer mass memory.[3]

However, as mentioned at the outset of this article, the invention of the laser in 1960 transformed, at a stroke of light, the field of data storage. The laser made possible optical storage, whose potential had been recognized for some time in theory.[4]

Soon after the advent of the laser, RADC began to investigate the possibilities of laser recorders and holograms for storage and retrieval of information with the goal of finding alternatives to magnetic computer disk memory. RADC tested thermoplastic tapes and silver-halide films along with lasers for possible use in recorders.[5] In 1966, RADC unveiled an electron and laser recording system and the following year began investigating with ARPA the feasibility of laser recorders for military use.[6]

In the 1970s RADC also explored ways to make computers more "user-friendly." One result, the Human-Readable/Machine-Readable microfilm mass memory system, stored both computer code and images on four-by-six inch

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[3]   *Ibid.*

[4]   *Ibid.*

[5]   *Ibid.*

[6]   *HRL*, p. 107.

microfiche plates. A laser scanned words and pictures and automatically converted them into computer code.[7]

RADC also explored computer-generated holography to store data on microfilm. Holography not only permitted the storage of greater amounts of information but also reduced the chances of its accidental destruction.[8]

RADC researchers were particularly interested in a technique called "wide band recording" that involved applying laser and electron beam technology to high density recorders across a wide range of frequencies.[9] RADC demonstrated a wideband analog recording readout system in 1969. The system featured an electron beam recorder that scanned a silver halide film storage medium. The film was coated with a plastic scintillator and emitted light when exposed to the electronic scanner. A photomultiplier then converted the light into electronic signals. In April 1970, a laboratory model was demonstrated at the National Telemetering Conference. The system handled ten times the frequency range of then current magnetic tape equipment.[10]

The advent of compact disk technology also created new opportunities for wideband recording. An early prototype used an argon laser to record and play back digital data from a 12.5 inch plastic optical disk. By the early 1980s, RADC had undertaken investigating the potential of optical disk technology.[11]

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[7]   *Ibid.*

[8]   *Ibid.*

[9]   *HRL*, p. 106.

[10]   *HRL*, p. 107.

[11]   *HRL*, pp. 107-8.

RADC worked with RCA to produce the so-called Optical Juke Box. The eight-foot wide and three-foot deep box held 100 non-erasable 14-inch diameter laser disks that provided storage for one trillion bytes of data. (For instance, the side of one disk could store as much information as a typical set of encyclopedias.) Accessing data took a mere six seconds.[12]

The Air Force seized upon the optical storage technology of the Juke Box for determining target coordinates in "near-real-time." This represented a considerable improvement over earlier film-processing that took about 15 minutes to calculate.[13]

In 1984, RADC and the NASA Marshall Space Flight Center, Huntsville, AL, began testing two Jukeboxes. The object was to combine optical disk storage with the Defense Mapping Agency's (DMA's) point positioning data bases. (NASA intended to use the Jukebox to process data sent by space probes.)[14]

With advances in technology, specifically the miniaturization of components and larger optical memories, opportunities emerged for adapting optical disks for Air Force tactical missions. RADC and Sundstrand Data Control Corporation began experiments with a tactical optical disk (TOD) the size of a bread box. Among the features of the TOD were erasable optical disks, which permitted repeated use. The TOD began flight testing in 1989. Successful testing led to its incorporation in the test regime of the Advanced Fighter Technology Integration

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[12]   *HRL*, p. 108.

[13]   *Ibid.*

[14]   *Ibid.*

(AFTI)/F-16 Close Air Support program. In 1992, TODs also flew aboard the Space Shuttle.[15]

In the 1990s research turned to studying the feasibility of three-dimensional memories that stored information in two-dimensional planes throughout a storage medium in order to increase storage capacity and speed. As a result of this research, holograms and bit-oriented memories emerged as two of the more promising possibilities for three-dimensional computer memories. Meanwhile, RADC and (from 1990) Rome Laboratory explored different methods for absorbing and recording light energy and new materials in which it could be stored. The latter included organic substances, even DNA, instead of integrated circuits.[16]

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[15]   *HRL*, pp. 108-9.

[16]   *HRL*, p. 109.

Panoramic Night Vision Goggle

USAF aircrews have been using night vision goggles (NVGs) in increasing numbers since the mid 1970s to gain tactical advantage through improved situational awareness and terrain avoidance. By the early 1990s, however, they were requesting NVGs with a wider field of view (FOV) and better image resolution. The limited FOV of existing NVGs made aggressive head scanning necessary for maintaining minimal situation awareness during night missions. Unfortunately, currently fielded military-aviation NVGs, such as the 40° circular FOV AN/AVS-6 and the AN/AVS-9, could not be upgraded because they used a pair of 18-mm image intensifier tubes to create the NVG's binocular image, and each tube had a fixed number of picture elements, or pixels. Thus, the larger the FOV, the more angular subtense per pixel, meaning that any additional FOV could only be achieved at the expense of resolution. Industrial and systems engineer Jeffrey L. Craig, manager of the Night Vision Operations Program at the Armstrong Laboratory, observed, "For years, it was thought that 40 degrees was the maximum field of vision night vision goggles could have without sacrificing resolution. Attempts to improve the system were focused on seeing better within that predetermined 40 degrees. Still, regardless of what improvements you make, it was like looking through a soda straw." Additional problems with existing goggles were a poor center of gravity and protrusions up to 6 inches in front of the wearer. The first of these difficulties led to extensive fatigue during long missions, while the second forced crew members to leave the goggles behind during emergency egress.[1]

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[1] Web page, J. Craig and L. Task, Armstrong Laboratory, and D. Filipovitch, Night Vision Corp., "Development and Evaluation of the Panoramic Night Vision Goggle," conference paper presented at the 1997 Society for Information Display Symposium, Boston, Mass., 12 May 1997, and reprinted in Tech report, Alan R. Pinkus, AFRL/HECV, et al., "Twenty-Plus Years of Night Vision Technology: Publications and Patents from the Crew System Interface Division of the Air Force Research Laboratory at Wright-Patterson Air Force Base, Ohio AFRL-HE-WP-TR-2003-0048" [hereafter cited as "Twenty-Plus Years"], Mar 03, pp. 365-368; available on the Internet at http://www.hec.afrl.af.mil/Publications/night/Resource/365-368.pdf on 26 Oct 05. The

Nonetheless, additional research and development on NVGs, especially with wider FOVs moved forward. While field-testing the Night Operations Visual Aid (NOVA-8) goggle system, for example, which provided a 60° FOV in early 1995, Craig studied the improvements this goggle offered over the Aviator Night Vision Imaging System (ANVIS) and began believing that an even better system could be developed. His conviction led the laboratory's Human Engineering Division (AL/CFHV) to award, in May 1995, an $80,000 Phase I small business innovative research (SIBR) contract to Night Vision Corporation (NVC), of Costa Mesa, California, to construct a conceptual demonstrator Panoramic NVG (PNVG) device. NVC's product, fabricated in November 1995, operated on the same general principles as a standard NVG, but it was constructed in a novel way. By using four third-generation 16-mm image intensifier tubes (two per ocular) and combining their imagery through folded optics, this new device produced an overlapping 30° by 40° center FOV for binocular vision, and left and right eye monocular FOVs of 35° by 40°, for an overall horizon size of 100° by 40°—a 160 percent increase over existing NVGs. Moreover, while weighing about the same as existing NVGs, the PNVG had a shallower frontal profile, giving it an improved center of gravity and better egress clearance. Thus the wearer might be able to eject with the PNVG in place and use it afterwards to assist in escape, evasion and rescue—something that could not be done with then-operational systems. For his conceptualization and development of the PNVG, Craig received the 1998 Harold Brown Award in the area of research and development.[2]

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quotation is from Web page, Bob Van Elsberg, "Turning Night Into Day," *Flying Safety,* Mar 97, available on the Internet at http://afsafety.af.mil/magazine/htdocs/marmag97/mar010.htm on 25 Oct 05.

[2] *Ibid*; Report, Danny Filipovitch, et al., Night Vision Corp., "Final Report - SBIR Phase I Panoramic Night Vision Goggle (PNVG)," AL/CF-SR-1996-0001, Dec 95.

The promising results of the PNVG's Phase I performance led the predecessor of the AFRL Human Effectiveness Directorate's Visual Display Systems Branch (HECV) to follow with a three-year Phase II effort beginning in late 1996. Initially funded with a SBIR award of $750,000, NVC also received supplemental 6.3 funding from AFRL's Helmet-Mounted Sensory Technologies program office at Wright-Patterson AFB. In all, the contractor earned about $6 million for its PNVG Phase II efforts.[3] Between October 1998 and March 1999 NVC delivered twelve PNVG advanced technology demonstrator (ATD) devices, in one of two varieties: (1) seven examples of a low-profile goggle, designated PNVG I, for ejection-seat aircraft crew members; and (2) five examples of a heavier, more traditionally styled goggle, designated PNVG II, for transport and helicopter aircrew and for ground personnel. The latter was designed to attach to any existing ANVIS mounting system. Both models featured the same 100° by 40° FOV as NVC's demonstration device. The 18-mm image intensifier tubes, however, were replaced with new fourth-generation 16-mm tubes developed in December 1997 by HE's Visual Displays Systems Branch and ITT Night Vision of Roanoke, Va.[4] The latter were substantially lighter (26 grams vs. 45 grams), had fewer parts, and promised better resolution. The new tube was such an

3   Report Jack Fiore, et al., Night Vision Corp., "Panoramic Night Vision Goggle (PNVG), SBIR Phase II," AFRL-HE-WP-SR-1999-0004, Jul 99; Article, Michael Mecham, "NASA, USAF Progress on Panoramic Goggles" [hereafter cited as "USAF Progress"], *Aviation Week & Space Technology*, vol. 153, no. 7, 14 Aug 00, p. 56; Web page, n.a., "Jeffrey L. Craig Receives Harold Brown Award for Panoramic Night Vision Goggle Development," n.d., available on the Internet at http://www.afrl.af.mil/successstories/1998/award_rec/ar6.pdf on 26 Oct 05.

4   Web page, Jeffrey L. Craig, AFRL/HECV, and Eric E. Geiselman, Logicon Technical Services, Inc., "Further Development of the Panoramic Night Vision Goggle," paper presented at the 36th Annual Symposium of the SAFE Association, Phoenix, Ariz., 14-16 Sep 98, and reprinted in "Twenty-Plus Years," pp. 369-374, available on the Internet at http://www.hec.afrl.af.mil/Publications/night/Resource/369-374.pdf on 26 Oct 05.

improvement that it was predicted to become the next industry standard—meaning that it would be produced in large, cost-cutting quantities.[5]

As the devices were delivered, they were subjected to a variety of ground-based, safety-of-flight tests conducted by personnel at Wright-Patterson AFB; Gentex East in Carbondale, Pa.; National Testing Systems in Saugus, Calif.; Dayton T. Brown; Reynolds Industries, Inc.; the Ohio Air National Guard's 162nd Fighter Squadron; Nellis AFB in Nevada; and Boeing in St. Louis, Mo.[6] Beginning in March 1999 F-15C and F-15E pilots of the 422nd Test and Evaluation Squadron at Nellis AFB, Nevada, conducted fixed-wing flight tests.[7] The testing included interoperability evaluations of various PNVG I configurations in combination with another HECV-sponsored Visually Coupled Acquisition and Targeting System (VCATS) test product. Some PNVG I configurations extended that daytime-only system's capabilities into darkness.[8] Overall, the flight test participants found that, as compared to the standard-issue NVG, the PNVG I was "very effective." Subsequently C-130 crewmembers of the 50th and 61st Airlift Squadrons at Little Rock AFB in Arkansas and C-5 crewmembers of the 3rd and 9th Airlift Squadrons and the 436th Air Wing at Dover AFB in Delaware tested

[5]   Briefing, Randall W. Brown and Jeffrey L. Craig, AFRL/HECV, "Panoramic Night Vision Goggle," 30 Mar 01, slide 13.

[6]   Web page, Timothy W. Jackson and Jeffrey L. Craig, AFRL/HECV, "Design, Development, Fabrication, and Safety-of-Flight Testing of a Panoramic Night Vision Goggle," paper presented at the Helmet-and Head-Mounted Displays IV Conference, Orlando, Fla., 5-6 Apr 99, and reprinted in "Twenty-Plus Years," pp. 391-402; available on the Internet at http://www.hec.afrl.mil/Publications/night/Resource/391-402.pdf on 26 Oct 05.

[7]   Web page, Eric E. Geiselman and Jeffrey L. Craig, AFRL/HECV, "Panoramic Night Vision Goggle Update," conference paper presented at the 37th Annual Symposium of the SAFE Association, Atlanta, Ga., 6-8 Dec 99; available on the Internet at http://www.hec.afrl.af.mil/Publications/safe00122 on 26 Oct 05.

[8]   For a discussion of the development of VCATS, see History, AFRL/HO, "History of the Air Force Research Laboratory October 1998-September 1999, Volume 1 – Narrative," 2001, pp. 242-254.

various PNVG II configurations and gave them an overall rating of "effective."[9] Researchers conducted additional testing of the PNVGs at NASA's Ames Research Center at Moffett Field in California (UH-60 Black Hawk helicopter pilots), the Air Mobility Warfare Center at McGuire AFB in New Jersey, and the U.S. Army Night Vision and Electronic Sensors Directorate at Ft. Belvoir in Virginia.[10]

By the end of 1999, several parallel developments had combined to advance PNVG in a slightly different direction. For example, helmet-electronics' mounts and couplings had become more interoperable, and the USAF's recent experience in Bosnia was a pointed reminder that night vision systems *must* incorporate effective laser eye protection that won't compromise cockpit situation awareness.[11]

These developments led HECV, with the United States Army Night Vision and Electronic Sensors Directorate (NVESD), to define a new ATD program, the Integrated Panoramic Night Vision Goggle (I-PNVG), for which a contractor was solicited on 16 December 1999. The program would optimize the wide FOV and

[9] Paper, Douglas L. Franck, Eric E. Geiselman, and Jeffrey L. Craig, AFRL/HECV, "Panoramic Night Vision Goggle Flight Test Results," conference paper presented at the Helmet- and Head-Mounted Displays V Conference, Orlando, Fla., 24-25 April 2000, and reprinted in "Twenty-Plus Years," pp. 381-389; available on the Internet at http://www.afrl.af.mil/Publications/night/Resource/381-390.pdf on 26 Oct 05.

[10] Paper, Zoltan Szoboszlay, et al., NASA Ames Research Center, "A Comparison of the AVS-9 and the Panoramic Night Vision Goggle during Rotorcraft Hover and Landing," presented at the 57th International Annual Forum of the American Helicopter Society, Washington, D.C., 9-11 May 01; News release, NASA Ames RC Public Affairs Office, "Vision Helicopter Goggles," Jun 00, available on the Internet at http://www.nasa.gov/centers/ames/news/releases/2000/00images/nightgoggles00/gogpixi nfo.html on 27 Oct 05; "USAF Progress."

[11] For HE's efforts to support USAF laser eye protection requirements before and during Operation ALLIED FORCE, see History, AFRL/HO, "History of the Air Force Research Laboratory October 1998-September 1999, Volume I – Narrative," 2001, pp. 264-273 and 278-280.

image resolution through trade studies: the solicitation called for a horizontal FOV of 80° or more and a vertical FOV and binocular overlap of 36° or more. The desired product had to incorporate laser eye protection and fit and comfort improvements. Its imagery displays needed to be fully compatible with VCATS and similar systems and, be ejection-safe. Most of all, it needed to pay attention to reliability, maintainability, supportability, interoperability, and especially affordability.[12]

On 13 April 2000, AFRL announced that Insight Technology, Inc., of Londonderry, N.H., had received a two-year 6.3 Program Research and Development Award of $6.4 million for the I-PNVG, with the Air Force providing two-thirds and the Army one-third of that amount. Contract "deliverables" included 25 test units for the Air Force and 20 for the Army, with ITT Night Vision supplying the image intensifier tubes.[13] An agreed-upon compromise between FOV and resolution for I-PNVG was set at 95° by 38°, and I-PNVG would provide for laser-hardening by several different means, including filters and optical limiters.[14] The first weight and space-equivalent I-PNVG 1 mock-ups were

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[12] For the program announcement in *Commerce Business Daily*, see Web page, n.a., "A – SOL: INTEGRATED PANORAMIC NIGHT VISION GOGGLE (PNVG)," 20 Dec 99, available on the Internet at http://www.fbodaily.com/cbd/archive/1999/12(December)/20-Dec-1999/Asol001.htm on 28 Oct 05; Briefing, Randall W. Brown and Jeffrey L. Craig, AFRL/HECV, "S&T Affordability Review," 24 May 00.

[13] For the contract announcement, see Web page, U.S. Dept. of Defense, "DefenseLINK News: Contracts for April 7, 2000," 7 Apr 00, available on the Internet at http://www.defenselink.mil/contracts/2000/c04072000_ct171-00.html on 25 Oct 05.

[14] For the important role played by AFRL's Materials and Manufacturing Directorate in developing laser eye protection materials, some of which would be incorporated into IPNVG, see History, AFRL/HO, "History of the Air Force Research Laboratory October 1997-September 1998, Volume I – Narrative," 2000, pp. 411-416.

scheduled for delivery in May 2001, with the first operational test models to follow three months later.[15]

General Michael E. Ryan, the USAF Chief of Staff, viewed a briefing by HECV on I-PNVG progress in 2000. On 21 September, he took a direct hand in accelerating PNVGs towards an early acquisition decision, telling program officials to "Get' this into the field fast!" This directive led the Aeronautical Systems Center to announce the establishment of a 6.4-funded PNVG program whose primary objective was to "rapidly field" a baseline PNVG that would "provide an expanded field of view over current systems, provide protection from lasers, be compatible with existing laser eye protection technologies, and provide a growth path to an ejection capable version."[16]

After the 422nd Test and Evaluation Squadron at Nellis AFB conducted additional PNVG tests in 2003, the ASC announced on 16 Apr 2004 that it was awarding Insight Technology Inc. a $13,007,796 firm fixed price contract to provide 255 Block 1 PNVGs and associated support equipment adapters by October 2005. (Later awards through July 2005 brought the total units ordered to 440.) On 25 April 2005 AC-130 gunship and MC-130 Combat Talon aircrews of AF Special Operations Forces aircrews received the first 20 units, which included an auto-gating feature that operates independently on each of the four image intensifier tubes. (This feature protects pilots from visual degradation if and when

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[15]   Paper, Jeffrey L. Craig, AFRL/HECV, "Integrated Panoramic Night Vision Goggle," conference paper presented at the 38th Annual Symposium of the SAFE Association, Reno, Nev., 9-11 Oct 00, and reprinted in "Twenty-Plus Years," pp. 375-380; available on the Internet at http://www.hec.afrl.af.mil/Publications/night/Resource/375-380.pdf on 26 Oct 05.

[16]   For the original program announcement in *Commerce Business Daily*, see Web page, n.a., "SOL: 16 – PANORAMIC NIGHT VISION GOGGLE (PNVG) PROGRAM," 22 Nov 00, available on the Internet at http://www.fbodaily.com/cbd/archive/2000/11(November)/27-Nov-2000/16sol015.htm on 25 Oct 05.

they encounter bright light sources such as flares. The tube exposed to such a source would automatically reduce gain, while the other tubes would allow the pilot to retain visual acuity and situational awareness.) Five days earlier F-15 and F-16 pilots at Nellis flight tested the Block IV PNVG, which integrates the goggles with the Joint Helmet Mounted Cueing System (JHMCS).[17]

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[17]   Web page, U.S. Dept. of Defense, "DoD News: Contracts for April 16, 2004," 16 Apr 04, available on the Internet at http://www.dod.gov/contracts/2004/ct20040416.html on 28 Oct 05; Web page, 1st Lt. David Cromwell, ASC/PA, "Special Ops Receives Night Vision Goggles," 25 Apr 05, available on the Internet at http://ascpa.public.wpafb.af.mil/Newsreleases/2005newsreleases/0529.htm on 25 Oct 05.

Partial and Full Pressure Suits

Aircrews flying at high altitudes have to be protected if a pressurized aircraft cabin is punctured by enemy fire or springs a leak due to structural failure. Sudden depressurization would cause the blood of crew members to expand and develop nitrogen bubbles. The resulting excruciating pain would destroy the ability of the crew to control the aircraft.[1]

As the altitudes at which military aircraft operated increased in the 1930s, both the Army Air Corps (AAC) and the Navy recognized the need for a flexible, reliable pressurized flying suit for its pilots. On October 10, 1939, the AAC initiated MX-117, a classified project whose goal was to develop a full-pressure suit that would protect the human body to an altitude of 30,000 meters (100,000 feet). During the early 1940s project leader Major John Kearby and other personnel of the Army Air Forces Materiel Command's Aero Medical Laboratory (AML) at Wright Field flight-tested various suits in a B-17 Flying Fortress bomber and other types of aircraft over the air proving ground at Eglin Field on the west coast of Florida. Designed by B. F. Goodrich, Bell Aircraft, Goodyear, U.S. Rubber, and National Carbon for protection of the human body up to an altitude of 30,000 meters (100,000 ft), they generally carried the XH designation (X for experimental and H for high altitude). Tight-fitting and constructed of a strong inelastic cloth that enveloped the pilot, they became balloon-like when inflated with a supplied pressure of about 24.1 kPa (3.5 psi) above the prevailing atmosphere. Most of these early suits were stiff and uncomfortably warm, making arm and leg movement impossible and requiring constant ventilation to maintain proper body temperature. These characteristics prevented airmen, among other things, from operating a Norden bombsight or camera. As a result,

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[1]   Book, Lloyd Mallan, *Suiting Up for Space: The Evolution of the Space Suit* [hereafter cited as *Suiting Up*], (New York: The John Day Company), 1971, p. 74.

the Army Air Forces cancelled its full-pressure suit project on October 29, 1943, and turned its attention to the partial pressure suit, while the Navy concentrated on full pressure suit research.[2]

Working under a study contract issued by AML, Dr. James Paget Henry (1914-1996), an assistant professor of aviation medicine at the University of Southern California, in 1944 began developing a partial-pressure emergency suit that would keep an airman alive until an aircraft whose cabin had lost pressurization could get down to lower altitudes. A pair of modified canvas puttees was laced tightly around the calves of the legs. Light nylon-web tights, extending from the waist to the knees, were form-fitted and laced tightly against the flesh. A suit of antigravity coveralls, fitted from the waist to the ankles with a bladder that could be inflated for additional pressure was worn over the other components. An inflatable pressure vest was worn over the coveralls. Tight-fitting gloves and sleeves made of a nonstretchable material covered the hands, and a sealed pressure-breathing helmet protected the head. The suit also used a capstan principle--a combination of inflatable tubes along the sides of the arms, chest, thighs, and legs that pulled the suit's fabric tightly against the body to apply mechanical counterpressure against the internal expansion of gases and water vapor in the blood vessels and tissues. After Henry successfully demonstrated the suit in an AML altitude chamber at a simulated height of 95,000 feet in late 1945, the David Clark Company, of Worcester, Massachusetts, under a purchase order from AML, began manufacturing the resulting "S-1 Partial Pressure Suit" in early 1946. A year later Captain H. H. Jacobs successfully tested the suit in an AML altitude chamber to an unprecedented simulated height of 106,000 feet.[3]

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[2] *Ibid*, pp. 100-112; Book, Lillian D. Kozloski, *U.S. Space Gear: Outfitting the Astronaut* [hereafter cited as *Space Gear*], (Washington: Smithsonian Institution Press), 1994, pp. 15-19.

[3] *Suiting Up*, pp. 74-82, 113, and 117-118; *Space Gear* p. 26. For a brief biographical profile and photograph of Henry, see Web page, n.a., "The New Mexico Museum of

Henry about this time joined the laboratory (as chief of acceleration and stress in the Biophysics Branch), and he and other AML personnel subsequently developed several improved partial-pressure suits. The S-2 had a full-head sealed helmet (eliminating the need for an oxygen mask), larger capstan tubes for counterpressurization along the arms and the sides of the body, and an oxygen bottle strapped to the wearer's thigh for emergency bailouts at high altitudes. Lighter because it had no anti-g bladder, it could be worn in comfort for longer periods. When Capt. Chuck Yeager became the first person to break through the sound barrier as he piloted the rocket-powered Bell XS-1 experimental aircraft on October 14, 1947, he was wearing an S-2 suit.[4]

As Henry and his colleagues improved the S-2 suit, it evolved into the T-1. Normally worn uninflated, it had an inflatable bladder across the belly and thighs (to protect the wearer against high-gravity forces) and an adjusted size of capstan tubing. Its associated K-1 helmet, designed by AML, was comprised of a two-piece outer hard shell and a protective faceplate, or visor, that provided the wearer with considerably better visibility than that of earlier helmets. The T-1 assembly also provided anti-g suit protection and contained earphones, a microphone, oxygen valves, a defroster, and an oxygen bailout cylinder. The Dave Clark Company in 1947 began manufacturing the T-1 suit in twelve different sizes. Manipulation of the laces in front of the legs and knees as well as along the thighs and sides enabled the suit to be fitted on 92 percent of flying personnel.[5]

Frank Everest, a test pilot assigned to the Flight Test Division at Wright-Patterson AFB, made the first operational emergency use of the T-1 suit on

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Space History – Inductee – James P. Henry," n.d., available on the Internet at http://www.spacefame.org/henry.html on 16 Sep 05.

[4]   *Suiting Up*, p.120.

[5]   *Suiting Up*, pp. 119-121; *Space Gear*, pp. 28-29.

August 25, 1949, when the canopy of a Bell XS-1 aircraft developed a crack and split as he reached supersonic speed at an altitude of 21,000 meters. As designed, the suit, in reaction to the loss of cockpit pressurization, immediately inflated and provided oxygen and limited protection until Everest brought his plane to an altitude below 6,000 meters (20,000 feet), where he could breathe more or less normally. The T-1 also permitted Douglas Aircraft test pilot William Bridgman, in a Douglas D-558-II Skyrocket naval aircraft, to reach a record altitude of 79,494 feet on August 15, 1951. The T-1A, which incorporated larger capstan tubing and an improved anti-g bladder, was first ordered in March 1956. It was worn with an improved MA-1 helmet that could be worn with both partial- and full-pressure suits. Problems with weight, oxygen leaks, and an unstable sealing system, however, limited use of this helmet in combat situations.[6]

Development of aircraft flying long hours at high altitude spurred the anthropometry unit at Wright Field to design new partial-pressure suits to protect the crews of these aircraft. The MC-1 suit, with pressurized gloves and a rubberized inflatable bladder across the chest and abdomen to relieve muscle strain and reduce fatigue, was designed specifically for crews of the B-36 Peacemaker bomber. For the crews of the B-52 Stratofortress bomber, which would be flying up to eleven hours above 46,500 feet and up to three hours above 50,000 feet, the Air Force in 1956 mandated the MC-3, an originally experimental suit built by the Clothing Branch of the AML that had a bladder that wrapped around the whole trunk of the body. The MC-4A, the last partial-pressure suit manufactured, incorporated anti-g protection bladders. Designed for fighter aircraft crews, it was declared the standard by January 1960.[7]

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[6]   *Suiting Up*, pp. 117 and 119; *Space Gear*, pp. 28-29. The date of Everest's emergency use of the T-1 suit is from a chronology of his XS-1 and X-2 flights attached to Web page, Mark Wade, "Frank K Everest" entry, *Encyclopedia Astronautica*, available on the Internet at http://www.astronautix.com/astros/everest.htm on 16 Sep 05.

[7]   *Suiting Up*, pp. 124-133; *Space Gear*, pp. 29-31.

More demanding Strategic Air Command requirements increased the need for a full-pressure suit. After the Air Force rejected the model 2-A, made by Goodrich for the Navy, because it lacked mobility and proper ventilation and was cumbersome to don and doff, AML in the spring of 1955 issued contracts for suits based on new designs to the International Latex Corporation and the David Clark Company. The suit designed by the latter, designated as the XMC-2-DC and later as the A/P22S-2, incorporated a soft slip-net linknet nylon layer that restrained the inflated pressure capsule around the wearer (thus providing mobility and comfort but preventing the suit from ballooning). It soon became the standard Air Force full pressure suit and was used by pilots of the X-15 research aircraft between 1959 and 1968; it was also a precursor of the suit chosen by the National Aeronautics and Space Administration (NASA) for astronauts in the Project Gemini program.[8]

Another contribution of AML to the development of the full-pressure suit was the design, by Environment Section chief Hans Mauch in 1954, of an air-cooled ventilated undergarment worn underneath the suit. A blower connected to the electrical power of the aircraft blew air through tiny pinholes in the inside layer (adjoining the wearer's skin) of a multilayed liner. Larger holes in the outermost layer allowed the air to be sucked out, thus creating a constant circulation of air around the wearer's body.[9]

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[8] *Space Gear*, pp. 31-33.

[9] *Suiting Up*, p. 150.

Phased Array Radar

One of the most revolutionary developments in the history of radar is the emergence of active electronically scanned phased array (AESA) radars in the second half of the 20th century.[1] Major contributions to this development were made by the Air Force Research Laboratory (AFRL), most particularly, AFRL's Information Directorate (AFRL/IF) and its predecessor organizations, the Rome Air Development Center (1951-1990) and the Rome Laboratory (1990-1997), and AFRL's Sensors Directorate (AFRL/SN) and its predecessor organizations, especially the Air Force Avionics Laboratory (AFAL).[2]

The word "radar" is an acronym for radio detection and ranging. It describes the use of radio range frequencies for long-distance detection of the presence of objects otherwise invisible to the naked eye or beyond the range of sight.

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[1]   Active, electronically scanned phased array radars differ from mechanical radars in that they have no moving parts (such as a rotating antenna "dish"). Instead, a phased array has from several hundred to several thousand transmit/receive modules that can be electronically actuated to scan one or multiple targets simultaneously. It is thus more versatile than mechanical radars and is less likely to experience catastrophic failure, thus giving it a greater mean time between critical failure (MTBCF). For more on phased array radars, see articles and reports cited below.

[2]   The Air Force Avionics Laboratory (AFAL) was formed between 1959 and 1963 from several smaller laboratories of the Wright Air Development Center (WADC), 1951-1959. In 1975, the laboratory became part of the Air Force Wright Aeronautical Laboratories (AFWAL). In 1988, AFWAL was reorganized as the Wright Research and Development Center (WRDC) and the Avionics Laboratory's Electronic Technology Division became an independent laboratory, the Electronic Technology Laboratory. In 1990, WRDC became the Wright Laboratory (WL) and the Electronic Technology Laboratory was renamed the Solid State Electronics Directorate. In 1996, the directorate was remerged with WL's Avionics Directorate. See Study, Dr. James F. Aldridge, ASC/HO, "A Historical Overview of the Mission and Organization of the Wright Laboratory, 1917-1993," Nov 1994, pp. 16-17, 20f, and 24f; History, ASD/HO, "History of the Aeronautical Systems Division, CY 1988," July 1989, vol. 1, pp. 253-60; History, ASC/HO, "History of the Aeronautical Systems Center, FY 1996," April 1997, vol. 1, p. 185; History, ASC/HO, "History of the Aeronautical Systems Center, FY 1997," April 1998, vol. 1, p. 247.

Historically, radar has been used for everything from ship and airplane navigation, to aerial mapping, to ground, sea, and aerial warfare.

The discovery of the radar phenomenon occurred in the late 19th century, in Germany, by Heinrich Hertz (1888).[3] In 1900, a German engineer suggested using radar for ship navigation in fog. In the early 1920s engineers at the U.S. Naval Research Laboratory (NRL) detected the passing of ships using a primitive bistatic radar device. However, their experiments were discontinued due to the lack of management interest and funding.[4]

In the mid 1930s radar detection of aircraft was under development by several countries simultaneously, including the U.S., Great Britain, Germany, France, the Soviet Union, and Italy. British efforts under Robert Watson-Watt reached maturity by the outset of World War II. The ground-based Chain Home Defense radar, established at Watt's instigation, provided early warning of incoming German aircraft during the Battle of Britain. The wartime British invention of the cavity magnetron also enabled the development of practical microwave airborne radio sets.[5]

In the U.S., radar experimentation, from the mid 1930s and during World War II was conducted by MIT's Radiation Laboratory, the NRL, and the Army's Signal Corps laboratories at Fort Monmouth, New Jersey, and Wright Field, Ohio. Cooperation with the British during World War II led to rapid advances, particularly in airborne radar technology and equipment. One of most significant

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[3] Article, n.a., "Radar," *Collier's Encyclopedia,* vol. 19, 1996, p. 593.

[4] Article, Merrill I. Skolnik, "Fifty Years of Radar" [hereafter cited as "Fifty Years"], *IEEE Proceedings*, vol. 73, 1985, p. 182.

[5] "Fifty Years," p. 182; Article , David K. Barton, "A Half-Century of Radar," reprint from *IEEE Transactions in Microwave Theory Technology*, vol. MTT-32, Sept 1984, pp. 1161-1170.

radars developed in the U.S. during the war was the Eagle AN/APQ-7 X-band mechanically scanned phased array radar.[6]

Development of phased array radars continued after World War II. Early postwar research concentrated on development of large ground-based radars, designed primarily for use in detecting the approach of enemy aircraft and ballistic missiles. The USAF's Rome Air Development Center (RADC), established in 1951, pioneered ground-based phased array radar work.[7] Research and development underwritten by RADC contributed to the AN/FPS-108 Cobra Dane, AN/SPQ-11 Cobra Judy, and AN/FPS-115 Pave Paws phased array radars.[8]

Phased array radar development was enabled by advances in electronic technology in the immediate postwar period. Most important was the invention of the solid-state transistor by Bell Laboratories in 1948 that inaugurated the age of solid state microelectronics.[9] Invention of the transistor was followed a decade later by the invention of the integrated circuit (IC), discovered independently and simultaneously by Robert Noyce and Jack Kilby.[10]

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[6]   "Fifty Years," p. 184.

[7]   Book, Thomas W. Thompson, *The Fifty-Year Role of the United States Air Force in Advancing Information Technology: A History of the Rome, New York, Ground Electronics Laboratory*, Studies in Twentieth Century American History, vol. 10 (Lewiston, Queenston, Lampeter: Edward Mellen Press,) n.d., pp. 34-35.

[8]   Fact sheet, n.a., "Pave Paws," Jan 1979.

[9]   Article, n.a., "Transistor," *Encyclopedia Americana* (Danbury, Connecticut: Grolier), 2000, vol. 27, p. 7.

[10]   See Book, T. R. Reid, *The Chip: How Two Americans Invented the Microchip and Launched a Revolution* (New York: Simon & Schuster) 1984.

Solid state microelectronic technology allowed development of active, electronically scanned phased array antennas. Such radars are able to detect small targets, simultaneously track multiple targets, and prevent jamming. Due to the "graceful degradation" of the arrays' several hundred to several thousand transmit/receive elements, solid state arrays are also more reliable and maintainable than gimbaled mechanical dish radars.[11]

The first solid state phased array radar for airborne application was underwritten by the Air Force Avionics Laboratory in 1964. Called Molecular Electronics for Radar Applications (MERA), the program was initiated to advance the state-of-the-art in silicon microwave integrated circuits, but was soon expanded to apply this technology in demonstrating the feasibility of developing an active electronically scanned phased array radar antenna for use in fighter aircraft.[12]

The success of MERA led the Avionics Laboratory to sponsor the Reliable Advanced Solid State Radar (RASSR). RASSR had two objectives: to build a solid state phased array antenna that could meet operational requirements and, second, to demonstrate the increased reliability of a solid state phased array antenna over conventional, mechanical radars then in use. Overall, RASSR was also a success.[13]

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[11]   Paper, Ike Chang, "The Rise of Active-Element Phased-Array Radar," The Rand Graduate School, P-7747-RGS, 1991; Paper, Russell Logan, Texas Instruments, "Airborne Solid State Phased Arrays: A System Engineering Perspective," n.d.

[12]   Report, Dr. James F. Aldridge, ed., "USAF Research and Development: The Legacy of the Wright Laboratory Science and Engineering Community, 1917-1997" (draft) [hereafter cited as "USAF R&D"], n.d., pp. 109-110. Report, James E. Cunningham and E. V. Farinholt, Texas Instruments, "Molecular Electronics for Radar Applications, Phase II," AFAL-TR-69-334, Nov 1969.

[13]   Report, n.a., "Reliable Advanced Solid-State Radar," AFAL-TR-74-321, 15 Aug 1969.

The success of MERA and RASSR were conditioned by the limitations of the silicon substrate in the transistors of their transmit/receive (T/R) modules. However, during the course of the 1970s, advances were made in another substrate material, gallium arsenide (GaAs), whose development had been underwritten by the Air Force Materials Laboratory and Avionics Laboratory at Wright Field since the 1950s.[14] The development of GaAs field effect transistors (FETs) with sufficient power, low noise, switch and phase shifter devices, led to the development of T/R modules operating at 10 GHz fundamental frequency, a substantial improvement over silicon devices.[15]

At the same time, work continued on the use and operation of phased array radars in the Electronically Agile Radar (EAR) program. Although EAR was a "passive" electronically scanned array (ESA), meaning it used ferrite phase shifters to steer the beam, much was learned of the beam control and mode designs using electronically steered beams. The Avionics Laboratory sponsored the EAR program, which became the baseline for the B-1B APQ-164 Offensive Radar System.[16]

This breakthrough in device technology and success of EAR led the Avionics Laboratory to sponsor a third major solid state phased array program, nearly 20 years after MERA. Called the Solid State Phased Array (SSPA) program, it involved design, fabrication, and ground testing of an SSPA sized to fit the F-15 fighter.

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[14]   Point paper, AFWAL/ML to ASD/CC (Lt Gen Thomas H. McMullen), "Gallium Arsenide Technology," 16 Apr 1984.

[15]   "USAF R&D," p. 111.

[16]   E-mail, Donald L. Tomlinson, AFRL/SNO, to James F. Aldridge, AFRL/HO, "Phased Array Radar – longbrake input.doc," 10 Jan 06; E-mail, Mark R. Longbrake, AFRL/SNR, to William E. Moore and Donald L. Tomlinson, AFRL/SNO, "[Solid State Phased Array] Write-Up Coordination Draft," 3 Jan 06 [hereafter cited as E-mail, "Phased Array Radar"].

The SSPA program was successful in demonstrating the superior capabilities of the SSPA over conventional mechanical radars, in particular a mean time between critical failure (MTBCF) in excess of 70,000 hours.[17] However, the cost of component fabrication, particularly of the T/R modules, was deemed excessive at $12,000 per module. Further advances in technology—both in device design and fabrication techniques—were necessary before an SSPA was practical.[18]

Following testing, the SSPA antenna transitioned, in 1988, to the Avionics Laboratory's Ultra Reliable Radar (URR) program. There it was integrated with other subsystems to form a complete airborne fighter radar system. The URR consisted of the SSPA, receiver/exciter power supplies, and a common signal processor. The URR was used subsequently as a test-bed for SSPA radar development for the F-22.[19]

Work continued in the AFRL Sensors Directorate (AFRL/SN) and the Materials and Manufacturing Directorate (AFRL/ML) to reduce the cost and weight and to improve performance of AESAs. Manufacturing technology programs in ML attacked the cost and yield of building the T/R modules. The Multi-Function Integrated RF System (MIRFS) program in SN worked to expand the capabilities of AESA based radars. the MIRFS system was the risk reduction

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[17] Report, n.a., "Solid State Phased Array: Final Report for Period April 1983 to May 1988," AFWAL-TR-89-5014, Apr 1989.

[18] In order to bring down the cost of T/R modules, the Avionics Laboratory, with funding provided by the Defense Advanced Research Projects Agency (DARPA), sponsored the Microwave Millimeter Wave Monolithic Integrated Circuit (MIMIC) program, from 1987-1995. MIMIC technology succecded in reducing the cost of T/R modules to an affordable $800 per module. See "USAF R&D," p. 112.

[19] Background paper, Mr. Williams, AFWAL/AARM, "Ultra Reliable Radar (URR)," 4 Nov 86; Statement of work, n.a., "Ultra Reliable Radar," 2 Mar 84.

and technology demonstration effort for the Joint Strike Fighter (F-35) APG-81 radar system.[20]

Over the past three decades much work has been done to reduce the size, weight, and cost of the T/R modules. The modules have gone from the relatively long cylindrical SSPA modules to the brick approach where the T/R functions are implemented in a multilayer "circuit board" that can be attached parallel to the array face (which could be additional layers of circulators and radiators.) This leads to manufacturing approaches that can reduce cost such as a reel-to-reel assembly of the different functional layers following the selection of various sizes of arrays. This can be thought of as the "RF by the yard." This also makes the arrays relatively flexible so conformal installation is possible. The future of AESAs is more than just radar: it is flexible, conformal, and possibly structurally integrated into multi-function RF systems.[21]

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[20]   E-mail, "Phased Array Radar."

[21]   *Ibid.*

Rare-Earth Permanent Magnets

Rare-earth permanent magnets, whose manufacture has developed into a $2 billion/year industry, were invented as part of an in-house research project conducted by the Electronic and Magnetic Materials Section of the Thermophysics (later, Thermal and Solid State) Branch of the Physics Laboratory (later, Material Physics Division), Directorate of Materials and Processes (Materials Center), Aeronautical Systems Division, Air Force Systems Command in the 1960s. The rare earths are the lanthanide group of elements--which, in the periodical table, begin with lanthanum (La; atomic number 57) and end with lutetium (Lu; 71)--and the chemically similar elements scandium (Sc; 21) and yttrium (Y; 39). A contemporary research program, the atomic-powered aircraft program, needed to determine the basic fundamental properties of a great number of rare-earth alloys and intermetallic compounds, because the rare earths are typically fission products. Materials scientist Dr. Karl J. Strnat led the branch's studies of these materials during the 1960s. Born in Vienna, Austria, he earned a Ph.D. degree in applied physics from the Vienna Institute of Technology in 1956. After working as a teaching assistant at the institute from 1953 to 1957, Strnat came to the laboratory in 1958 under the auspices of Project Paper Clip. After resigning from the Air Force in 1968, he served as a professor of engineering at the University of Dayton until his death on 1 May 1992.[1]

Early work of the branch included an investigation of the diffusion of impurities in thermoelectric materials at high temperatures and in severe temperature gradients. Branch members also performed extensive measurements of conductivity, susceptibility, and other electrical and magnetic properties on a great number of rare-earth alloys and intermetallic compounds.

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[1]   Book, AFRL/ML, *History of the Air Force Materials Laboratory, vol. 2, pt. 2—Landmark Technology Programs 1960 to 1990* [hereafter cited as *Landmark Technology*], Report No. ASC/PA#ASC-00-0912, Mar 00, pp. 49 and 52.

The data developed enabled them to establish many binary phase diagrams for rare-earth materials.[2]

The work required the construction of new research equipment. For example, Strnat's team built a recording apparatus to measure electrical resistivity of metal samples at temperatures up to 1500 C, which enabled them to study anomalies found in temperature-versus-resistivity curves of some binary alloys containing a rare-earth element as one constituent.[3]

In early 1962, the branch began seeking, among the rare earth transition metal intermetallics, permanent magnets that combined high performance, minimum volume, reduced weight, and an operating capability over a broad temperature range. By early 1963 branch members had completed fabrication of a small levitation-melting furnace that would be used to prepare contamination-free magnetic alloys from the highly reactive rare-earth metal constituents. This radio frequency induction unit, which could melt and chill cast 50 to 80 gram quantities in a vacuum or protective atmosphere, was designed in such a way that an ingot could be removed and the furnace could be reloaded without breaking the vacuum. With this apparatus, branch members prepared for the first time a number of intermetallic compounds of iron with rare-earth metals and studied their crystal structure, melting behavior, magnetic properties, and electrical resistivity. These studies led to corrections in the binary phase diagrams of iron with cerium (Ce), praseodymium (Pr), and neodymium (Nd).

[2] Report, n.a., "Materials Central Physics Laboratory Report: January 1960-July 1960," n.d., as reported in *Landmark Technology*, p. 50.

[3] Report, n.a., "A Condensed History of the Air Force Materials Laboratory/Directorate" [hereafter cited as "Condensed History"], n.d., p. 14.

The researchers determined that the compounds $CeFe_2$, $CeFe_7$, $PrFe_7$, and $NdFe_7$ were ferromagnetic at room temperatures and metallic conductors.[4]

In 1964 Strnat and his colleagues narrowed the field of candidate materials to the noncubic, transition-metal-rich, intermetallic phases of the rare earths (including yttrium) with cobalt (Co) and possibly iron. They recognized that many strongly magnetic compounds could be formed between yttrium and the rare earths, on the one hand, and cobalt on the other. Perkin-Elmer Corporation, under contract, delivered single crystals of $YCo5$ and $Y2Co17$ in early 1965, and later that year Strnat's team made critical measurements of their magnetocrystalline anisotropy.[5]

By early 1966 his team, which at this time included Dr. Werner Osterag, Lt. Gary Hoffer, John Olson, and Dr. Alden E. Ray of the University of Dayton, recognized two potentially useful classes of intermetallic compounds from their in-house program. They envisioned compounds of the composition R_2Co_{17} (where R is yttrium, cerium, praseodymium, neodymium, or lutetium) as having promise as useful ferromagnetic materials for magnetic memory applications, such as magnetic tapes or computer memory elements. They also determined that compounds of the composition RCo_5 (where R is cerium, praseodymium, samarium [Sm], or cerium–rich or yttrium-rich mischmetal) were permanent-magnet materials that offered better performance than Alnico magnets and at much lower cost than platinum-cobalt (PtCo) magnets. Further studies of the RCo_5 alloys revealed they have extremely high uniaxial anisotropy, single easy

[4]   Report, n.a., "Materials Central Physics Laboratory Report: January 1962-June 1962," n.d.; Report, n.a., "AFML History, Materials Physics Division, January 1963-June 1963," n.d., p. 2, both as reported in *Landmark Technology*, p. 50.

[5]   Report, n.a., "AFML History: Material Physics Division, July 1964-December 1964," n.d., pp. 2 and 4; Report, n.a., "AFML History: Material Physics Division, January 1965-June 1965," n.d., pp. 1-2; and Report, n.a., "AFML History: Material Physics Division, July 1965-December 1965," n.d., pp. 2 and 4; all as reported in *Landmark Technology*, pp. 51-52.

axis, and high saturation and Curie points and that they are the only materials, other than the ferrites and PtCo, that are really permanent magnets (that is, immune to self demagnetization), a property considered particularly important in dynamic applications, such as electric motors and generators.[6]

Section members determined $SmCo_5$ to have the highest value of coercive force (21,700 Oersted) of any material under investigation. In 1968 they found that coating the $SmCo_5$ particles with zinc or tin improved performance while precluding deterioration of the coercive force over time. By late 1969, they determined that $SmCo_5$ magnets have energy products two or three times greater than those of Alnico and coercive forces up to ten times greater. They could thus replace Alnico in many applications with less material, resulting in space and weight savings. In late 1969 the Materials Laboratory's Manufacturing Technology Division awarded contracts to the Raytheon Corporation and the General Electric Company to establish the necessary manufacturing processes for pilot production techniques and to supply quantities of $SmCo_5$ magnets.[7]

$SmCo_5$ magnets are regarded as a key technology that enabled a revolutionary change in the development of equipment offering high performance and high efficiency for microwave processing, inertial navigation, spacecraft navigation and orientation, and computers. They offer weight reductions up to 90 % and have improved operational reliability by a factor of 40. $SmCo_5$ replaced PtCo in traveling wave amplifiers in commercial communications satellites, where they performed focusing much better at a lower cost. $SmCo_5$ magnets in a

[6]   Report, n.a., "AFML History: Material Physics Division, January 1966-June 1966," n.d., p. 13; and Report, n.a., "AFML History: Material Physics Division, July 1966-December 1966," n.d., p. 8; all as reported in *Landmark Technology,* p. 53.

[7]   Report, n.a., "AFML History: Material Physics Division, January 1968-June 1968," n.d., p. 5; Report, n.a., "AFML History: Material Physics Division, July 1969-December 1969," n.d., p. 4; Report, n.a., "AFML History: Manufacturing Technology Division, July 1969-December 1969," n.d., p. 12; all as reported in *Landmark Technology,* pp. 54-55 and 57.

generator provide a dependable fly-by-wire power source for the B-2 bomber, supplying 50 amps steady state at 28 volts. They are also used in the brushless motors of surgical drills and saws. These tools, operating at 75,000 revolutions per minute, generate high torque and withstand high autoclave sterilization temperatures, and they offer, because of the small size of the motor magnets, low mass and small size for ease of handling in hospital operating rooms. $SmCo_5$ and other rare earth magnets made possible the miniaturization of computer hard-disk drives, leading to the development of laptop and palmtop computers.[8]

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[8] "Condensed History," pp. 15-17.

Reliability of Electronic Aerospace Systems

The reliability and maintainability of aerospace systems have been much emphasized during the past decade. However, they have been a concern of Air Force operators for over half a century. There has been no area of greater concern than in electronics, the "brains" of modern aerospace systems. From the very beginning, the Information Technology Directorate of the Air Force Research Laboratory (AFRL/IF) and its predecessor organizations, the Rome Air Development Center (1951-1990) and the Rome Laboratory (1990-1997), have been deeply involved with military electronics reliability issues. [1]

In 1950 the Air Force first commissioned the RAND Corporation to investigate the whole question of electronic reliability. At the time, the solid state transistor had been invented only several years previously and vacuum tube devices still dominated military electronics systems. RADC sponsored a number of studies that examined the effects of shock, vibration, and temperature on reliability of electronic components. Other studies examined the connection between reliability and electrical and thermal stress and environmental factors like salt and moisture. Some of these early studies even explored the possibility of developing self-repairing circuits. [2]

RADC developed methods and equipment for maintaining fielded electronic systems. In 1953, the Center developed an automatic fault locator system for the AN/TPS-1D tactical radar and subsequently adapted variants for other radars.

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[1]   Book, Dr. Thomas W. Thompson, *The Fifty-Year Role of the United States Air Force in Advancing Information Technology—A History of the Rome, New York, Ground Electronics Laboratory* [hereafter cited as *HRL*], Studies in Twentieth Century American History, vol. 10 (Lewiston, Queenston, Lampeter: The Edwin Mellen Press), n.d., p. 136.

[2]   *Ibid.*

RADC also explored extending the use of automatic test equipment to other electronic systems.[3]

In addition to avoiding component failure, RADC explored how to make electronic systems operate so as not to interfere electromagnetically with each other, something called "compatibility." In 1961, RADC developed a cavity band pass filter that removed unwanted signals from high-power radars. It also developed the AN/MSM-63 spectrum measurement system that identified potential interference of different types of equipment before leaving the factory. RADC also developed "time-sharing" techniques to minimize interference. In 1966, RADC summarized its experience in avoiding or minimizing interference in an "interference notebook" that it published for users.[4] In 1969, the Center unveiled an Interference Cancellation System that eliminated interference that occurred when high power UHF transmitters operated near sensitive receivers. This made it possible for transmitters and receivers to operate in the same location.[5]

RADC also led efforts to render "fail safe" the electronics underpinning the nation's nuclear systems. Particular attention was given to the delivery of electronics components and systems from the factory to the field.[6]

As early as 1955, RADC published what became the "bible" of the reliability handbooks, *Reliability Factors for Ground Electronic Equipment*. This work emphasized the importance of design, while making allowance for the "human factor" and the need to think of military electronic equipment in terms of

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[3]   *HRL*, p. 137.

[4]   *HRL*, pp. 137-8.

[5]   *HRL*, pp. 138-9.

[6]   *HRL*, p. 141.

"systems" instead of only individual components. The *Handbook* included a mathematical section that presented curves for calculating reliability. It was regularly updated to incorporate the state-of-the-art in ground electronics. The *Handbook* was the forerunner of many subsequent publications addressing electronic reliability.[7]

Also in mid 1950s, RADC published Exhibit 2629[8] that provided a formula for computing the mean time between failure (MTBF) of electronic systems based on the number of tubes and parts in electronic equipment. Exhibit 2629 required formal "accept-reject" testing of electronic equipment as a condition for Air Force purchase and also stipulated that contractors provide an estimate of the equipment's reliability no later than 30 days after contract award. Another exhibit was Exhibit 2693 that set forth requirements for reliability during the production of electronic equipment. It served as a benchmark for Air Force Military Requirements 26474, *Reliability Requirements for Production of Ground Electronic Equipment*. The RADC *Notebook* (see above) contained the first valid technique for predicting reliability. Finally, on the eve of the solid-state revolution inaugurated by invention of the integrated circuit, in 1959, the *Reliable Preferred Solid State Functional Divisions* identified circuits whose reliability would be increased through the introduction of solid state components.[9]

With the gradual replacement of vacuum-tube equipment with solid-state microelectronic devices, new methods of reliability testing had to be developed. Solid state devices were much smaller and could be produced in much greater

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[7] *HRL*, pp. 141-2.

[8] "Exhibits" were documents generally attached to requests for contract bids, such as those that laid down reliability requirements. *HRL*, p. 143.

[9] *HRL*, pp. 142-3.

quantities than vacuum-tube devices. RADC was in the forefront of developing techniques for testing the new devices in the quantities required.[10]

RADC initiated a program for determining the "physics of failure" of electronic components. The Center studied solid state substrate materials at the molecular and atomic levels and developed mathematical models that predicted the behavior of substrate materials. In 1965, RADC published the *Reliability Physics Notebook* that detailed basic failure mechanisms in materials and their relation to the degradation and failure of electronic devices.[11]

In order to study new solid state device technology at first hand, RADC developed a number of in-house facilities. In 1961, it built a microelectronics laboratory, complete with a "clean room" for fabricating and testing microelectronics components. RADC soon added an epitaxial reactor for growing layers of silicon and an electron-beam microscope for testing microcircuits. In 1968, RADC built a new 80,000 square-foot electronics laboratory.[12]

Among RADC's in-house contributions to reliability research, one of the most impressive was the development, in 1966, of an automatic circuit tester. In addition to automation in testing, RADC also pioneered accelerated testing of microelectronics devices in the early 1970s.[13]

In 1968, RADC published *Military Standard 883*, the first military standard for screening microcircuits, which set forth uniform methods for the testing of

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[10] *HRL*, p. 140.

[11] *HRL*, pp. 145-6.

[12] *HRL*, pp. 146-7.

[13] *HRL*, p. 149.

microelectronic devices. Also in 1968, RADC published the *Handbook of Accelerated Life Testing.*[14]

In 1967, RADC set up a quick reaction capability (including quick reaction teams) for failure analysis of microelectronic semiconductor devices. One task involved testing integrated circuits for the Minuteman Missile program. In 1968, a Department of Defense Reliability Analysis Center (RAC) was set up in RADC to serve as a repository for the collection and distribution of information on microelectronic and semi-conductor devices and parts. The Illinois Institute of Technology Research Institute operated the facility under a RADC contract. Within a few years, RAC served as the DOD focal point for the dissemination of microcircuit reliability data. Among the systems it supported were the Minuteman, Atlas, and Titan intercontinental ballistic missiles, the F-111, the Ballistic Missile Early Warning System (BMEWS), and communications systems.[15]

In 1969, RADC established a separate division for reliability and compatibility. At the same time, the Center undertook reliability projects with the National Aeronautics and Space Administration (NASA), the National Security Agency (NSA), and the Federal Aviation Administration (FAA). RADC analyzed microcircuits on the Minuteman III and the F-111 Mark II avionics subsystem. RADC also served as trouble-shooter for electronics aboard the C-5A cargo plane and the Navy's Trident submarine.[16]

RADC led efforts to test the compatibility of solid state devices within microelectronic components and systems. There were potential compatibility

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[14]   *Ibid.*

[15]   *HRL*, pp. 150-51.

[16]   *HRL*, p. 151.

problems among thousands of microelectronic circuits as well as devices manufactured by different companies. In the course of the 1970s, RADC built several anechoic chambers for resolving potential compatibility issues between the electronics of advanced weaponry and munitions, such as the AIM-9J Sidewinder missile, and the on-board electronics of the air vehicles carrying them. Indeed, in 1973, RADC was designated Air Force program manager of Have Note, which was to test the susceptibility of air-launched weapons, satellites, drones, and reentry vehicles to radio frequency influences.[17]

RADC harnessed improvements in digital computers over the course of the 1970s for simulating and predicting failure modes in electronic components and systems. The Optimum Reliability and Component Life Estimator (ORACLE), for instance, simulated the effects of temperature and electrical stresses on reliability. RADC also developed computer models that predicted the number of undetected software errors in a given computer program at a given time.[18]

During the 1980s and 1990s, RADC (and its successor, the Rome Laboratory) turned its attention to examining discrepancies that sometimes occurred in microelectronic devices between their performance in the laboratory and in the field. A joint RADC and NASA investigation, in 1985, into the shutdown of a Space Shuttle just prior to take off found contamination of the Shuttle's central processing unit with human spittle. The discovery led to an investigation into manufacturing of microelectronics components and found that this kind of contamination was by no means unusual and that additional measures had to be implemented to lessen the possibility of future instances of contamination.[19]

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[17]   *HRL*, p. 152.

[18]   *HRL*, p. 153.

[19]   *HRL*, p. 154.

As very high speed integrated circuits (VHSICs) were introduced into Air Force electronics systems during the 1980s, RADC began to develop testing techniques for VHSIC circuits, such as the Tester Independent Support Software System (TISSS). TISSS provided the software languages necessary for generating test programs for VHSIC components and served as an archival data base for storing device and module designs and test data. An outgrowth of TISSS, called the Waveform and Vector Exchange Standard (WAVES) became an industry standard. RADC also developed software that automated the process of generating test specification requirements and test programs for VHSIC Phase I devices.[20]

The advent of computer-aided-design (CAD) in the 1970s permitted reductions in the time required to assess reliability. One such tool was the General Electromagnetic Model for the Analysis of Complex Systems (GEMACS), which supported antenna pattern and radar cross section research. It was soon modified into an engineering and design tool for assessing radar component reliability.[21] RADC and Rome Laboratory enlisted CAD tools in the 1980s and 1990s to analyze stresses within microcircuits and to design power densities and circuits for very large scale integrated (VLSI) circuits. Ultimately, modeling and simulation helped measure the effects of electromagnetic energy on monolithic microwave integrated circuits (MMICs), VHSIC, and electro-optical devices.[22]

In the 1990 to 1997 period, Rome Laboratory embarked on the test and evaluation of commercial off-the-shelf (COTS) microcircuit devices to determine where these devices could reliably be utilized in military systems. By enhancing

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[20]   *HRL*, p. 155.

[21]   *HRL*, p. 156.

[22]   *HRL*, p. 157.

the highly accelerated stress test (HAST), it was possible to assess which commercial devices could survive under military temperature, shock, vibration, and humidity conditions. The success of these tests to determine the applicability of certain commercial devices, resulted in the addition of these devices to the approved military standard parts list. The availability of these devices spurred reductions in cost and the insertion of the latest technology rapidly into military systems. MIL-STD-883 , first published in 1968, has served for nearly 40 years as the test standard of choice for microcircuit devices throughout the world.[23]

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[23] Email, Mark Lomery, AFRL/IFOI, to Dr. James F. Aldridge, AFRL/HO, "Your Review is Required . . .Atchs, RELIABILITY – draft.doc," 14 Nov 05, comments by Eugene Blackburn.

Satellite Communications

Satellite communication (SATCOM) emerged during the last quarter of the twentieth century as one of the most important developments for commercial and military operations. Many of the most significant contributions to this development were made by the Air Force Research Laboratory's (AFRL's) Information Directorate (IF) and its predecessor organizations, the Rome Air Development Center (1951-1990) and the Rome Laboratory (1990-1997).[1]

The notion of communicating real time from any point on the globe to any other via artificial satellites orbiting about the earth was broached by science fiction writer Arthur C. Clark, in 1945.[2] The following year, the RAND Corporation suggested that the Air Force could make use of artificial satellites for reconnaissance, weather prediction, and communications.[3] However, the reality of such satellites remained in the realm of science fiction and think tank "what ifs" for another decade before the nascent "space race" between the Soviet Union and the United States produced an infusion of funding and sense of urgency to such undertakings.

In 1955, the United States announced plans to launch an artificial satellite into earth orbit during the 1957 International Geophysical Year (IGY). The following day the Soviet Union made a similar announcement and, in fact, beat

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[1] Article, Thomas W. Thompson, "Rome Laboratory: A Brief History," *Rome Laboratory Technical Journal*, vol 1, June 1995, pp. 1-6; History, ASC/HO, "History of the Aeronautical Systems Center, FY 1997," vol. 1, May 1988, p. 247.

[2] Book, Thomas W. Thompson, *The Fifty-Year Role of the United States Air Force in Advancing Information Technology: A History of the Rome, New York, Ground Electronics Laboratory* [hereafter cited as *HRL*], Studies in Twentieth Century History, vol. 10 (Lewiston, Queenston, Lampeter: The Edwin Mellen Press), n.d., p. 71.

[3] *HRL*, p. 72.

the U.S. to the punch on 4 October 1957 with the launch of *Sputnik I*. The effect of *Sputnik*, not only on world opinion, but within U.S. political, military, and scientific communities was electrifying. This was all the more so after the U.S.'s attempt to launch *Vanguard I*, on 6 December 1957, ended in failure.[4] The Soviets had, in the meantime, launched *Sputnik II*, a half-ton satellite that seemed to indicate a Soviet superiority in ballistic missile development, a factor more worrying at the time to the U.S. military than the satellite itself.[5]

However much *Sputnik I and II* may have fueled fears about U.S. inferiority in ballistic missile development, they also spurred the development of communications satellites (COMSATs) by the U.S. military. Development of the latter had taken a decidedly back seat as late as 1957, when Air Force Chief Scientist, Dr. Theodore von Karman was rebuffed by an Air Staff more concerned with missile development than with his suggestion that the Air Force put COMSATs on its developmental agenda.[6] However, in the late 1950s, the Air Force lost the space mission to the National Aeronautics and Space Administration (NASA).[7] One of NASA's first projects was development of a COMSAT called Echo I.[8]

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[4] *HRL*, p. 73.

[5] Book, Michael H. Gorn, *Harnessing the Genie: Science and Technology Forecasting for the Air Force, 1944-1986* [hereafter cited as *Genie*], (Washington, D.C.: Office of Air Force History), 1988, p. 68. See Book, Jacob Neufeld, *Ballistic Missiles in the United States Air Force, 1945-1960* (Washington, D.C.: Office of Air Force History, United States Air Force), 1990.

[6] *Genie*, p. 68.

[7] NASA was created from elements of the National Advisory Committee for Aeronautics (NACA), established in 1915. The NACA had been responsible for major advances in aeronautics from the 1920s through the 1950s. See Book, Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915-1958* (Washington, D.C.: National Aeronautics and Space Administration), 1985, chapter 1.

[8] Echo I was essentially the brain-child of NASA engineer William O'Sullivan. *HRL*, p. 72. For a more in-depth treatment of RADC's contributions to Echo I, see Report,

Echo I was essentially a large balloon-like structure that inflated to 100 feet in diameter once it had been placed in orbit and reflected radio signals from its shiny, silvery surface. The concept of such a COMSAT had first been broached in 1954 by John R. Pierce of Bell Laboratories. According to Pierce, such COMSATs would serve as cosmic "relay towers," capturing frequencies in the 50 megahertz range as they passed out of the atmosphere and then reflecting them back to receiving stations on earth. These COMSATs would supplement transatlantic communications, which had already largely maximized the frequency range of radio telephones. [9]

Scientists and engineers at the Rome Air Development Center, Rome, New York, seized on the opportunity to cooperate with NASA in the development and testing of Echo I.[10] As Mr. Harry Davis, RADC technical director had observed around this time: "a knowledge of the dynamics of satellites . . . will . . . be important to the military engineer."[11]

By May 1959, RADC had planned a series of experiments with NASA for Echo I, which was launched into a 1,000 mile orbit on 12 August 1960. In preparation for the Echo I launch, RADC had set up several tracking sites. From the site in Trinidad, the Virgin Islands, RADC engineers bounced a radio signal off Echo I to a receiver station at Floyd, New York. The Air Force grandly styled it "the first intercontinental signal ever sent by satellite."[12] With no exaggeration,

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Thomas W. Thompson, RADC/HO, "The Echo One Experiment: The Beginnings of Air Force Satellite Communications," Air Force Systems Command Special Study (Griffiss AFB, Rome, NY), 1985.

[9]   *HRL*, p. 71.

[10]   *HRL*, p. 73.

[11]   *HRL*, p. 71.

[12]   *HRL*, p. 74.

Rome Laboratory historian Thomas W. Thompson wrote that "[t]he Echo I experiments ushered in a series of tests that permanently established [RADC's] role in military satellite communications research."[13]

RADC's cooperation with NASA on Echo I continued with Echo II, which was launched on 25 January 1964. RADC's Echo II tests included experiments with signal power, Faraday rotation, Doppler effect, and new modulation techniques. RADC also conducted studies concerning the increase of Echo II's reflective cross section and those of other passive COMSATs.[14]

Meanwhile, RADC also conducted tests on the Westford, an Air Force-sponsored COMSAT developed by the Lincoln Laboratory of the Massachusetts Institute of Technology (MIT). The Westford consisted of millions of tiny wires and was placed in a 2,000 mile polar orbit. RADC commissioned studies for the Westford that examined the type of ground terminals needed to operate such orbiting wire belts and their effectiveness if the attempt were made to jam signals.[15]

Echo I was a so-called "passive satellite," which merely reflected signals to a ground receiving station. During the 1960s, RADC began to explore with NASA the development of "active satellites" that could amplify signals before resending them to ground receivers, which, in turn could then be made smaller and more mobile. With the development of solid state microelectronics, active COMSATs became increasingly practical and common.[16]

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[13]   *Ibid.*

[14]   *HRL*, pp. 75-6.

[15]   *HRL*, p. 75.

[16]   *Ibid.*

In 1962, RADC began operating a mobile satellite communications terminal, touted by the Air Force as the world's first transportable terminal. In 1965, RADC used the terminal in a series of experiments with the active geosynchronous COMSAT SYNCOM III. The experiments centered on establishing methods for obtaining multiple communications links to the satellite. In 1966, RADC modified the terminal to conduct tests with the military's first satellite system, the Initial Defense Satellite Communications System (IDSCS).[17]

In 1967, RADC began conducting experiments with the Lincoln Experimental Satellites (LES) 5. Among the tests conducted were teletype messages to airborne, shipborne, submarine, and surface configuration terminals, a dozen in all. These tests continued in 1968 with the LES 6.[18]

The following year, RADC began testing with TACSAT I. RADC developed tests and specifications for TACSAT I and devised means to simulate the satellite terminal under operational conditions with the aim of identifying network management methods for minimizing communications congestion.[19]

In the 1970s, the Air Force developed (and deployed in 1979) the Air Force Communications System (AFSATCOM) to relay messages to and from nuclear forces and nuclear command centers. RADC made a number of important contributions to AFSATCOM. In 1973, the Center verified AFSATCOM's timing and synchronization concepts and analyzed AFSATCOM equipment at RADC's

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[17] *HRL*, p. 76.

[18] *Ibid.*

[19] *Ibid.*

Verona Test Site.[20] The following year, RADC built a UHF SATCOM terminal for AFSATCOM.[21]

During the decade of the 1980s and into the 1990s, RADC became involved in a major effort to give Air Force communication satellites extremely high frequency (EHF) capability under the Military Strategic Tactical and Relay (MILSTAR) program. In support of MILSTAR, RADC built a new experimental facility, called the Satellite EHF Research Terminal (SERT). RADC developed and evaluated airborne terminals for MILSTAR including tubes, amplifiers, antennas, and modems. Among the improvements emerging from this work were: acoustic charged transport devices, microelectronic devices producing high signal processing rates, impact ionization avalanche transit time (IMPATT) diodes, and field effect transistors (FETs) for distributing amplifiers within phased array antennas. The effort was aided by the development of extremely thin monolithic microwave integrated circuits (MMICs) that allowed the design of airborne satellite terminals that fit flush against aircraft thus satisfying both aerodynamic and low observable requirements. In support of MILSTAR, RADC also played a key role in the development, testing, and transitioning of an EHF hybrid airborne antenna, which scanned mechanically in azimuth and electronically in elevation. [22]

Other EHF efforts included testing of an EHF satellite adaptive array processor, an adaptive antenna for satellite receivers that incorporated "adaptive nulling," which distinguished between jamming and friendly communications. Finally, in 1994, there occurred a landmark event with the launch of the first

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[20] The Verona site became RADC's principal site for testing satellite communication in 1979. *HRL*, p. 77.

[21] *HRL*, p. 77.

[22] *HRL*, pp. 77-8.

military EHF network switched satellite, which conducted successful EHF transmission among ground and airborne terminals.[23]

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[23] *HRL*, pp. 78-9; E-mail, Mark J. Lomery/IFOI to Dr. James F. Aldridge, AFRL/HO, "Write-Ups for McFawn Project," 1 Dec 05.

Self-Healing Plastics

Being in the right place at the right time is not just a casual expression to AFOSR program managers. Part of their job is to attend what they consider to be the most promising research workshops and conferences in their field, so that they may scout out talented research teams with cutting edge program potential. Such was the case in 1998 when Dr. Ozden Ochoa, an AFOSR/NA program manager, attended a workshop where Dr. Scott White from the University of Illinois at Urbana-Champaign presented a paper on "self-healing plastic." After the presentation, Dr. Ochoa encouraged Dr. White to submit a funding proposal to AFOSR.[1] Dr. White did so shortly thereafter. Dr. Ochoa oversaw the processing of the proposal, and the research award was finalized in the fall of 1999.[2] Dr. White and his team were awarded an AFOSR grant for the sum of $334,539 for three years research.[3] Shortly thereafter, Dr. Ochoa moved on to another position and was replaced by Dr. H. Thomas Hahn, who enthusiastically followed up with this research endeavor. Dr. White's proposal detailed a process whereby microscopic cracks in aircraft structures could heal themselves.[4]

Dr. White and his colleagues had been discussing a self-healing approach to polymer-composites for several years and were acutely aware that, while

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[1]   Interview, Dr. Robert White, AFOSR/PIC, with Dr. Scott White, University of Illinois at Urbana-Champaign (UIUC), 10 Nov 2005.

[2]   Interview, Dr. Robert White, AFOSR/PIC, with Dr. Les B. Lee, AFOSR/NA, 24 Aug 2005.

[3]   Database document, n.a., "AFOSR Discoverer Data Base," 24 Aug 2005. p.10. White's initial proposal (#99NA165), under Contract # F49620-00-1-0094, was entitled, "Development of Self-Sealing Structural Composite Materials," p. 2. Also, see AFOSR/NA grant folder, White, et al., "Self-Healing Structural Composite Materials," Document # F49620-02-1-0080, 1999-2001.

[4]   Grant proposal, Scott White, UIUC, "Multiscale Modeling and Experiments for Design of Self-Healing Structural Composite Materials," # F49620-02-1-0080, June 1999.

polymer composites serve many useful purposes, they have one significant drawback. As noted by Dr. White, "...one longstanding problem has been their susceptibility to micro-cracking, where the micro-cracks eventually coalesce, become large cracks, and then catastrophic failure can occur with little forewarning."[5] The way to approach this issue became clearer to White when he thought of looking towards nature as a model to address this shortcoming— basically, how does nature behave in a similar situation? In retrospect, White reflects that it was a pretty obvious move to go in this direction—to look at the human body's response to an injury. So the concept of self-healing came out of that approach.[6]

Prior to being approached by Dr. Ochoa, Dr. White and his team were supported by seed money from the University of Illinois, but this internal funding only brought the program, "...to the point where it could be considered as a fully funded research topic." At that point Dr. White applied to both the National Science Foundation (NSF) and the Defense Advanced Research Projects Agency (DARPA) for funding to fully pursue what he and his team thought was a very promising technology. NSF and DARPA thought otherwise. In fact, Dr. White noted that one of the reasons DARPA turned the proposal down was that it was considered "too high risk."[7]

With the AFOSR grant in hand, White's team did not take long to produce significant results. It was in February 2001 that the team's seminal paper on "Autonomic Healing of Polymer Composites," was published in the journal *Nature,* and it gained worldwide attention. From the University of Illinois campus

[5]   Interview, Bob White with Scott White, 10 Nov 2005.

[6]   *Ibid.*

[7]   *Ibid.*

newspaper, to the Washington Post, to the London Guardian—this was big news.[8]

This initial success resulted in "groundbreaking research [that] demonstrated the ability to engineer high efficiency self-healing polymeric composites for Air Force applications."[9] In more practical terms, according to Dr. White, spherical microcapsules with healing agents would be embedded in aircraft material prone to stress cracks. When stress fractures eventually appear and cause the spheres to rupture, their contents would provide a self-healing bond to mitigate the damage.[10] Although this approach worked, there was an obvious drawback: the healing process only took effect in the immediate area of the sphere, and the supply of healing agent was limited—and thus began the search for a better approach. Dr. White's search for a better approach began in earnest in 2001, and AFOSR was there to support his effort.[11] Dr. B. Les Lee, a successor of Dr. Hahn at AFOSR, invited Dr. White to the 2002 Air Force Workshop on

[8] Article, S.R. White, et al., UIUC, "Autonomic Healing of Polymer Composites," *Nature*, vol. 409, 15 Feb 2001, pp. 794-797. A Google search reveals that there are over 300,000 articles on White's discovery in the year 2001 alone. Also see Brfg, H. Thomas Hahn, AFOSR/NA, "Mechanics of Materials & Devices," 16 Apr 2001, pp. 1- 7, 14, 15.

[9] AFOSR/NA grant folder, Scott White (PI), Jeffery S. Moore, Nancy R. Sottos, UIUC, "Multifunctional Polymers and Composites for Self-Healing Applications," Section 2, Abstract, Jan 2001, p. i.

[10] Interview, Dr. Robert White, AFOSR/PIC, with Dr. Scott White, UIUC, Feb. 12, 2001. Also see Abstract, Scott White (PI), Jeffery S. Moore, Nancy R. Sottos, UIUC, "Multifunctional Polymers and Composites for Self-Healing Applications," Jan 2001, p. i.

[11] Interview, Bob White with Scott White, 10 Nov 2005. Interview, Dr. Robert White with Dr. Les B. Lee, 24 Aug 2005; AFOSR/NA grant folder, Scott White, Section 5, Annual Report, 25 Oct 2004; Brfg, B. L. Lee, AFOSR/NA, "Mechanics of Materials & Devices," 26 Apr 2004, pp. 30-32.

Multifunctional Aerospace Materials, which handled a variety of topics including self-diagnosis, self-healing and capillary network type cooling of aircraft skin.[12]

As a follow-up of this workshop, a new research concept of the "next generation self-healing system" was formally presented to AFOSR by Dr. White and his colleagues.[13] For this particular endeavor, White sought to discover a technique for fabricating a three-dimensional microvascular network. In his proposal to AFOSR for a renewed grant, Dr. White proposed to "...explore new conceptual approaches to self-healing that enable continuous and unlimited supply of healing agents to the material throughout its useful life."[14] To achieve this ambitious goal, the research team would be required to embed microvascular networks—much like a human blood circulatory system—into the plastic materials.[15] Elaborating on future applications of this concept, White noted that these miniscule networks could work as compact fluidic factories in sensors, chemical reactors and computers.[16]

Within one year of the grant approval by Dr. Lee, White and his colleagues were able to produce a pervasive network of interconnected cylindrical channels

[12]   E-mail, Lee Byung-Lip, AFOSR/NA, to Robert P. White, AFOSR/PIC, "Final Review of Article," 17 Nov 2005.

[13]   AFOSR/NA grant folder, Scott White, UIUC, Proposal Number 02-NA-191, 22 Apr 2002, p. 19; Data Base Review, Scott White, UIUC, "AFOSR Discoverer Data Base," 24 Aug 2005; Grant proposal, Scott White, UIUC, Proposal No. 02NA050, "Multifunctional Polymers and Composites for Self-Healing," 21 Aug 2002.

[14]   AFOSR/NA grant folder, Scott White, UIUC, untitled, Proposal Number 02-NA-191, 22 Apr 2002, p. 19.

[15]   *Ibid*; Interview, Bob White with Scott White, 10 Nov 2005.

[16]   Interview, Nahaku McFadden, AFOSR/PIC, with Dr. Scott White, UIUC, 12 Nov 2003; Interview, Bob White with Scott White, 10 Nov 2005.

that ranged from 10 to 300 microns in diameter.[17] This network was built with a computer controlled syringe that deposited a unique ink that fabricated a multi-layered interlocking scaffold structure. As a research team member explained the process: "After the layer is generated, the stage is raised and rotated then another layer is deposited. This process is repeated until the desired structure is produced." White went on to state that: "Once the scaffold has been created, it is surrounded with an epoxy resin, and after curing, the resin is heated and the liquefied ink is then extracted, leaving behind a network of interlocking tubes and channels."[18] In his program report to AFOSR, White explained that this process leads to optimal flow structures.[19]

Under AFOSR support, White and his team are currently working to expand the suite of materials that self-heal. While the original demonstration used only an epoxy material, currently vinyl esters and silicon rubber are being employed as well. In addition, by utilizing the embedded microvascular structure and healing approach with these materials, research is ongoing to greatly expand the application range for these types of materials. As an example, in their original work on microencapsulated healing agents prior to the microvascular approach, these materials would not tolerate temperatures above 80 degree C. With new catalyst and healing agents employed with the new microvascular approach, material integrity can be assured up to approximately 180 degree C. Advances have also been made in ways to expedite the curing of materials much more

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[17] The initial grant proposal cited diameters of 10 to 500 microns. AFOSR/NA grant folder, Scott White, UIUC, untitled, Proposal Number 02-NA-191, 22 Apr 2002, p. 19.

[18] Interview, McFadden with Scott White, 12 Nov. 2003. Also see: Technical proposal, Scott White, UIUC, "Microvascular Autonomic Composites," in AFOSR/NA grant folder, untitled, FA9550-05-1-0346. p.11.

[19] AFOSR/NA grant folder, untitled, FA9550-05-1-0346, p. 10.

rapidly: while the old system required a cure time of ten hours to recover the full integrity of the material, new systems can reach full cure within seconds.[20]

A spin-off activity which resulted from the microcapsule-based self-healing work, and more directly concerned with a current Air Force application, is self-healing cryogenic tanks, a project that White's team is working on with the AFRL Space Vehicles Directorate at Kirtland AFB, NM. If made from polymer composites, these tanks suffer from micro-cracking due to the extreme heating and cooling cycles they undergo. If the micro-cracks breech the walls of the cryogenic container, the contents are lost. One possible cure is to employ a very thick tank or specialized tank liner to prevent leakage, but this adds weight. Working under the auspices of an AFOSR STTR grant, White's team is exploring the use of filament wound self-healing cryogenic tanks.[21]

Even more significant is what is in store for the future: increasingly integrated multi-functionality for these types of materials, so that they will not only heal in response to damage, but will also cool in response to heat load, or, conversely, heat when too cold. They can also be configured to be self-diagnosing, and be able to sense biological agents. Self-healing micro-electronic structures are also being investigated to obviate dielectric breakdowns because of thermal or mechanical cycling.[22] These exploratory research concepts were summarized in a vision statement made by Dr. B. Les Lee, an AFOSR/NA program manager, at the 2002 Annual Spring Review for Upper Management. He proposed to pursue a goal of creating "autonomic aerospace structures" which are capable of self-diagnosis, self-healing, self-cooling and threat neutralization. Based on this vision, Dr. Lee collaborated with his colleague at AFOSR/NL, Dr. Hugh DeLong, and formulated a topic "Biomimetic Composites for Autonomic Aerospace

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[20]   Interview, Bob White with Scott White, 10 Nov 2005.

[21]   *Ibid.*

[22]   *Ibid.*

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Structures" for the 2005 Multi-disciplinary University Research Initiative (MURI). A total of 25 white papers, many of which displayed extraordinarily innovative thinking, were received and six Finalists were selected including a research team led by Dr. White.[23]

In the summer of 2005, after a thorough evaluation by nine panelists, AFOSR awarded the University of Illinois at Urbana-Champaign (UI-UC), a five year, five million dollar Multi-disciplinary University Research Initiative (MURI) grant for further research in microvascular composites for autonomic aerospace structures. On 10 August 2005, Dr. Brendan Godfrey, Director of AFOSR, visited the Beckman Institute at UI-UC to present the grant in person, and he challenged the researchers to build upon their accomplishments and further their success by working with the other MURI participants, which include UCLA, Duke University and Harvard Medical School.[24]

Scott White, in reflecting on AFOSR funding, stated, "I cannot emphasize enough how critical AFOSR funding was to our program...it was the first funding that we had to adequately explore this concept. AFOSR saw a lot of potential and was willing to take the risk and they should reap the benefits as far as I am concerned. AFOSR funding was extremely critical."[25]

What began in 1998 as a high risk technology endeavor, resulted, less than two years later, in the possibility of a highly sophisticated approach to the autonomous healing of aircraft structures. Initially, White and his team developed and proved the concept of self healing plastic. Recognizing the extraordinary potential of their research, as well as the shortcomings of their

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[23]   E-mail, Lee Byung-Lip, AFOSR/NA, to Robert P. White, AFOSR/PIC, "Final Review of Article," 17 Nov 2005.

[24]   Press release, AFOSR/PIC, "Self-Protecting Aerospace Structures One Step Closer to Reality," 10 August 2005.

[25]   Interview, Bob White with Scott White, 10 Nov 2005.

initial approach, i.e., localized and limited healing properties, the team went on to design and prove the concept of a network-wide and unlimited healing agent protocol.[26]   Several AFOSR program managers managed this successful program, beginning with Dr. Ozden Ochoa, to Dr. Tom Hahn, and on to Dr. Les Lee, who was responsible for the initiation of an entirely new MURI, that will fully exploit the promise of this new technology. This program is an unparalleled testament to the high-risk, high-payoff philosophy of AFOSR program managers in support of the Air Force mission.

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[26]   *Ibid.* For a recent concise general overview of White's work see: Newspaper article, Greg Kline, "A Leap Forward in Technology," *The News-Gazette*, 11 September 2005, p. A-2.

Softer Rides for Spacecraft Payload Launches

For virtually as long as man-made spacecraft have been launched, these high-cost assets have been hard-mounted to the launch vehicle. In essence, this is similar to removing the shock absorbers from an automobile and mounting the tires directly to the frame of the vehicle. The vibration loads imparted to a spacecraft by a launch vehicle's motors during the launch phase can be severe, with potential damage to the craft that often results in mission failure and the loss of millions of dollars. As a result, spacecraft must be designed to withstand these intense shocks at the expense of additional mass and ground tested at very high vibration levels. Because a sizeable minority of spacecraft failures resulted from these excessive vibrations, and with new spacecraft requirements that would have to rely on a technology that had not changed for over three decades, scientists at the Air Force's Phillips Laboratory invented a revolutionary design in launch shock absorption.

In 1971, NASA released a report titled "A Study of First Day Spacecraft Malfunctions" which indicated that up to 45 percent of all spacecraft payload failures could be attributed to vibration or acoustic-induced damage. Vibration generally originated from three sources. Pyro-shock was a relatively small part of the problem, while a second source came from acoustics. But structural-borne vibrations accounted for the largest number of vibration induced first-stage spacecraft failures. Structural-borne vibrations occur when an engine's vibrations come up through the launch vehicle's structure and into the spacecraft. The severity of shaking, measured in terms of gravity (g), increased the farther away from the launch vehicle's center of gravity.[1]

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[1]   Interview, Dr. Barron K. Oder, AFRL/VSIH, with Eugene R. Fosness, AFRL/VS, 11 Dec 1997; History, "Close-out History of the Phillips Laboratory, 1 October 1996 – 30 October 1997" [hereafter cited as "Close-out History"], vol. I, 1998, pp. 741-742; Paper, Eugene R. Fosness, Keith K. Denoyer, Alok Das, and David B. Founds, "Whole-Spacecraft Isolation Development Efforts at the USAF Phillips Laboratory" [hereafter

The type and size of launch vehicle also affected the launch vibration and other factors, notably cost. In general, the smaller the launch vehicle, the worse the vibration. Among small launch vehicles, former Intercontinental Ballistic Missiles (ICBMs) have been selected to fly spacecraft into orbit. However, these vehicles, including the Minotaur I with a Minuteman II heritage (and the forthcoming Minuteman IV with a Peacekeeper heritage), were never designed to carry delicate payloads. With the large launch vehicles, which carry more than one satellite into space per launch, the higher a satellite sat in the stack of satellites in the payload area, the more gs it absorbed during launch. A spacecraft designer has to take all of these factors into account, including whether or not to fly the spacecraft on a smaller, less costly launch vehicle with a rougher ride or a larger, relatively softer ride on a more expensive launch vehicle. Any reduction in the level of the launch vibration could potentially reduce the overall cost of spacecraft design, testing, and operation. And with spacecraft missions becoming more complex, adding more sensors and other electronics with greater power and fuel demands, designers began to look for ways in which weight savings could be made, particularly from components that did not add to the goals of the specific mission.[2]

In the early 1990s, scientists at the Air Force's Phillips Laboratory began to investigate the possibilities of mitigating launch vibration. In 1993, the lab issued a Phase I Small Business Innovation Research (SBIR) grant to CSA Engineering to determine the feasibility of isolating a spacecraft's payload from the vibrations. Working with McDonnell Douglas and Ball Aerospace, who brought essential space operations-related expertise to the table, and using the medium-level Delta II launch vehicle as its model, CSA found that mitigation was not only possible

cited as "Whole-Spacecraft"], SSC97-IX-I, Proceedings of the 11th AIAA/USU Conference on Small Satellites, Sept 1997.

[2] Notes/comments, Benjamin K. Henderson, AFRL/VSSV, "SoftRide Launch Vibration Isolation System draft" [hereafter cited as "SoftRide"], 28 July 2005; Interview with Fosness, 11 Dec 1997; "Close-out History," pp. 742-743; "Whole Spacecraft."

but potentially highly useful. This analysis led to CSA's 1994 Phase II SBIR grant.[3]

CSA's Phase II task meant designing a passive isolation device to give the spacecraft isolation from lateral movement. CSA found that the payload attachment fitting or PAF, where the spacecraft attaches to the launch vehicle, was the logical place to reduce the structure-borne lateral dynamic vibrations. Instead of the usual solid aluminum PAF, the CSA-designed SoftRide system pieced together aluminum sections with large slits or gaps—the gaps provided the cushioned ride. These interfaces between spacecraft and launch vehicle acted as a soft spring and damper system, tuned to reflect a portion of the vibrational energy back into the launch vehicle. The frequency response of the interface was designed to minimize vibration at frequencies that are predicted to cause damage to components of the spacecraft. Additionally, this approach could be expanded for use with other passive designs, newer active designs, or hybrid systems that combine both passive and active elements. In 1996, McDonnell Douglas, working with Honeywell, CSA, and Loral on an Air Force contract, designed and developed an isolation strut device that could mitigate axial vibration and complement the lateral isolation device.[4]

About the same time, Air Force Major Maurice Martin transferred to the Space and Missile Systems Center's (SMC) Small Launch Office from the Phillips Lab launch vibration isolation team. Working with the Multi-Service Launch System (MSLS), Major Martin concluded the program's Minuteman launch system could benefit from the lab's new technology. The Minuteman launch vehicle, originally designed to send warheads through space, had been

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[3]   Interview with Fosness, 11 Dec 1997; "Close-out History," pp. 743-745; "Whole Spacecraft."

[4]   "SoftRide;" Interview with Fosness, 11 Dec 1997; "Close-out History," p. 752; "Whole Spacecraft."

converted to launch much more sensitive satellites. Although Phillips Lab briefed SMC on the new technology, a year's delay in procurement meant that SMC had gone on from MSLS to the follow-on Orbital/Suborbital Program (OSP). OSP needed to launch the National Reconnaissance Office STEX satellite, scheduled for 1998. However, STEX failed its coupled load safety analysis, which meant redesigning the spacecraft and spending millions more in corrections. The lab coordinated meetings with the spacecraft integrator, Ball Aerospace, and CSA. CSA agreed to conduct an analysis, which determined that a 10 to 15 pound isolation system could reduce the dynamic loads by a factor of three to four.[5]

With this successful model, SMC determined that the technology could work on other problem systems, notably a Naval Research Laboratory (NRL) satellite called GEOSAT Follow-On (GFO) that continually failed its safety analysis. Again, Phillips Lab facilitated meetings with SMC, NRL, systems integrator Ball Aerospace and the owner of the Taurus launch vehicle, Orbital Sciences Corporation. The GFO team, hoping to avoid losses of time and money in a major redesign of the satellite, wanted to use the technology. However, the lab informed them it had not been proven as yet. These customers then issued Phillips Lab scientists a challenge: they would agree to be the first customers to fly this device if the lab would design, build, test, and deliver a flight-qualified device within three-and-a-half months. The lab's hardware, validated by the contractor, first flew with the GFO launch on 10 February 1998. Although component isolation had been employed in the past, this was the first whole-spacecraft vibration isolation system ever flown on a launch vehicle. The SoftRide system reduced the average structural-borne vibrations on the spacecraft by a factor of five in the frequency range of interest while meeting all the launch vehicle and spacecraft flight requirements. Furthermore, mission managers estimated the cost savings in excess of $5 million in redesign costs. The second successful SoftRide flight protected the National Reconnaissance

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[5]   Interview with Fosness, 11 Dec 1997; "Close-out History," pp. 745-747.

Office's STEX satellite, launched atop a Taurus launch vehicle on 3 October 1998. Designers believed the addition of SoftRide technology saved the STEX program an estimated $15 million.[6]

This new SoftRide technology received almost immediate recognition and praise. Following the GFO launch, Phillips Lab scientists received numerous calls requesting information on the SoftRide technology. In March 1999, the commander of the Air Force Research Laboratory (AFRL), the single Air Force Laboratory created in 1997 from the joining of Phillips Lab and other Air Force R&D organizations, presented the Lieutenant General Thomas R. Ferguson Award to the lab team comprised of Dr. Keith Denoyer, Dr. Dino Sciulli, and Mr. Eugene Fosness, for their work in developing this low-cost, reliable shock-absorption system. Named for a former commander of the Aeronautical Systems Division, the award recognized "a significant achievement of individuals or teams in the movement of a newly developed technology to a customer for engineering development, application or insertion."[7]

Due to the individual nature of launch systems, as well as satellite launch requirements, AFRL Space Vehicles Directorate scientists adapted these SoftRide technologies to meet customer needs. Minotaur I missions utilize the decommissioned Minuteman II ICBM assets, and approximately 10% of the Minotaur I second stage motors have a significant lateral lurch load. Lab scientists developed a new SoftRide system, called Multiflex, with the capacity to mitigate axial and lateral vibration loads simultaneously. The first Multiflex SoftRide system successfully flew on the Minotaur I launch vehicle to protect the

[6]   Interview with Fosness, 11 Dec 1997; "Close-out History," pp. 746-748; "SoftRide."

[7]   Interview with Fosness, 11 Dec 1997; History, AFRL/HO, "History of Air Force Research Laboratory, October 1998 – September 1999," vol. I, Aug 2001, p. 606. News release, Dr. John Brownlee, AFRL/VS, "AFRL Scientists and Engineers Honored for Achievements in Space Technology," No. 99-09, 1 April 1999.

Joint Air Force Academy-Weber State University Satellite (JAWSAT) on 26 January 2000.[8]

The success of SoftRide technology has been demonstrated over and over with the launch of several satellites belonging to both government and civilian customers. SoftRide technology protected the Department of Energy's Multispectral Thermal Imager (MTI) program launched aboard a Taurus launch vehicle on 12 March 2000, and AFRL's MightySat II.1 hyperspectral spacecraft experiment, flown aboard a Minotaur I vehicle on 19 July 2000. Most recently, a SoftRide system protected AFRL's eXperimental Small Satellite-11 (XSS-11) carried aboard a Minotaur I on 11 April 2005. The XSS-11 mission was the first to make use of a vibration isolation system in the ground qualification phase, drastically reducing the loads experienced prior to launch and potentially increasing satellite longevity and reliability. And the system has been selected to protect other spacecraft, notably Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) flown aboard a Minotaur I vehicle.[9]

AFRL scientists then developed and flew the next-generation system called ShockRing. ShockRing, designed to mitigate higher frequency loads, enables a short-schedule retrofit approach to spacecraft isolation. The lab first used ShockRing technology aboard the Vibro-Acoustic Launch Protection Experiment (VALPE) series of flights aboard Terrier-Orion sounding rockets on 20 November 2002 and 20 August 2003 from NASA's Wallops Island facility. AFRL scientists are now developing the ShockRing device for Atlas V launch vehicles, with the first test of this device to protect the Air Force Academy's FalconSat-3 spacecraft

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[8]   "SoftRide."

[9]   *Ibid.*; Article, AFRL/XPTC, "Tab 2-Emerging Technologies: Low-Shock Separation System Dramatically Reduces Satellite Failures," *Air Force Research Laboratory Success Stories, A Review of 2000,* 2001, p. 75.

as a secondary payload on the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adaptor ring.[10]

Based on the overwhelming success of SoftRide in the small launch vehicle sector, AFRL scientists have worked with the MILSATCOM Joint Program Office to examine the feasibility of developing similar isolation systems for large launch vehicles such as the Delta IV and Atlas V. Initial analyses have shown that a modified SoftRide system has the potential to provide significant reductions in launch loads for primary payloads. As a result, the system is under consideration for use on future MILSATCOM spacecraft, and modified SoftRide flight hardware has already been tested and delivered for a Delta IV Heavy Launch Vehicle.[11]

AFRL scientists have determined that the performance of these passive launch vibration isolation systems might be improved through lowering the axial bounce frequency. However, this frequency is coupled with the sensitive satellite rocking frequency, which can interfere with the launch vehicle guidance system. Studies have shown that a hybrid launch vibration isolation system, employing both passive and active or semi-active components, could overcome these limitations. Currently, AFRL scientists are working with SMC to develop a hybrid system that could enable twice the performance of purely passive systems.[12]

[10] "SoftRide;" Article, AFRL/XPTC, "Tab 2-Emerging Technologies: Shock Ring Technology Impacts Future Spacecraft Programs," *Air Force Research Laboratory Success Stories, A Review of 2004*, 2005, p. 68.

[11] "SoftRide;" Article, AFRL/XPTC, "Tab 1—Support to the Warfighter: Providing Satellites a Smoother Ride to Orbit," *Air Force Research Laboratory Success Stories, A Review of 2004*, 2005, p. 77.

[12] "SoftRide."

With the successful launches using these SoftRide-related launch vibration isolation systems, the Air Force proved that this new lightweight, low risk, affordable, robust method would improve the chances for spacecraft to perform their missions. Spacecraft designers have already begun to take advantage of the greatly improved launch loads, and the reduced mass enables the use of lighter and smaller spacecraft bus structures, launch on lower-cost vehicles, or adding more mission-capability. Investigating these problems, providing SoftRide, Multiflex, and ShockRing solutions, and making new advances in the field attests to the continued commitment of AFRL scientists to provide superior launch vibration isolation for the nation's military, government, and commercial aerospace industry.

Software Engineering

The history of the modern computer revolves around two interconnecting developments: hardware and software. The Information Directorate of the Air Force Research Laboratory (AFRL/IF) and its predecessor organizations, the Rome Air Development Center (1951-1990) and the Rome Laboratory (1990-1997)[1] have played a key role in developing computer software that was more reliable, cost-effective, and responsive to the needs of the United States Air Force.

In the late 1960s, the Rome Air Development Center (RADC) developed a software program known as the On-Line Pattern Analysis and Recognition System (OPLARS). The program, operating on a CDC 1604 computer system and a Honeywell 6180 processor, analyzed signals to identify patterns. Every situation produces some kind of pattern, whether sound, flashing light, or some other electromagnetic disturbance. When stored in a computer, these patterns could be recalled at some subsequent time and then used to identify the phenomenon. Thus, once OPLARS discerned a pattern, it could store it in its memory and then use this for future recognition. The Air Force hoped to use OPLARS in its reconnaissance, surveillance, and intelligence missions.[2]

RADC also conducted research into developing software for parallel processing, which involved assigning several computers to study a problem

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[1] See Article, Dr. Thomas W. Thompson, "Rome Laboratory: A Brief History," *Rome Laboratory Technical Journal,* June 1995, pp. 1-6; Book, Dr. Thomas W. Thompson, *The Fifty-Year Role of the United States Air Force in Advancing Information Technology—A History of the Rome, New York, Ground Electronics Laboratory* [hereafter cited as *HRL*], Studies in Twentieth Century American History, vol. 10 (Lewiston, Queenston, Lampeter: The Edwin Mellen Press), n.d.

[2] *HRL,* p. 122.

simultaneously. RADC researchers were particularly interested in the potential application of parallel processing to "associative memory" techniques, which promised to speed up computer operations. The Center established a facility for testing parallel processing concepts, including software. Researchers turned particular attention to making software portable among different computer systems as well as more reliable (see below).[3]

In addition to pioneering new software systems for Air Force applications, such as OPLARS, and more generic concerns, such as parallel processing and software reliability, RADC also turned its attention to *reducing the cost* of software, which had begun to escalate during the 1970s. Indeed, by mid decade, the Department of Defense (DOD) was spending three times as much money on computer software as on hardware.[4]

An opportunity to control escalating software costs came to RADC in 1969, when the Air Force directed RADC to improve the Air Force's programming language for command and control, Jules' Own Version of International Algebraic Languages, or JOVIAL, for short.[5] Time is money, and initially RADC increased the speed at which JOVIAL compilers operated. Center researchers developed a software tool that assessed the usefulness of JOVIAL compilers. The JOVIAL Compiler Implementation Tool, or JOCIT, was the best known project in the development of automated production. Of more significance in the long term,

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[3] *HRL*, p. 123.

[4] *Ibid.*

[5] JOVIAL was specifically developed for military aircraft avionics using the Military Standard (MIL-STD) 1750A processor. JOVIAL was the Air Force's standard (MIL-STD 1589) for embedded systems during the late 1970s and early 1980s when the majority of the Air Force's currently fielded weapon systems were developed. See Article, n.a., "JOVIAL LIVES!: Official Home Page of the USAF JOVIAL Program Office," n.d., at www.jovial.hill.af.mil/header.html, as of 4 Nov 05 and Article, n.a., "JOVIAL History," n.d., at www.jovial.hill.af.mil/support.html, as of 4 Nov 05.

RADC also developed automated techniques for the production of compilers. Eventually, RADC's compiler research was incorporated in the World-Wide Military and Command and Control System (WWMCCS) and the National Emergency Airborne Command Post (NEACP).[6]

In addition to work on JOVIAL, RADC published a series of guidelines concerning computer programming, many of which were widely disseminated. One set of these guidelines, called the Structured Programming System, established step-by-step procedures for developing software codes. Meanwhile, RADC issued other publications that addressed the problem of verifying software reliability, like the Automated Verification System.[7]

In the 1980s, RADC participated in developing a compiler for Ada, the computer language designated by DOD as the standard language for its software systems. RADC also helped develop an Ada Test and Verification System. Another RADC effort was the Software Life Cycle Support Environment (SLCSE) under which the computer assisted preparation of software specifications, requirements, design, and testing, thus bringing closer the Air Force's goal of reduced software costs.[8]

Also during the decade of the 1980s, RADC began an examination of so-called artificial intelligence as a potential means for realizing the next major advancement in software engineering. In 1983, RADC initiated a program in artificial intelligence called the Knowledge Based Software Assistant (KNOBS), which used artificial intelligence paradigms for the development, evaluation, and

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[6] *HRL*, p. 124.

[7] *Ibid.*

[8] *Ibid.*

long-term maintenance of computer software.[9] KNOBS recorded the steps during software development and thus served as a permanent repository of its history. The testing of KNOBS "formalisms," or mathematical notations that computers used to interpret knowledge, continued through the 1990s.[10]

In addition to these larger efforts, RADC employed artificial intelligence software programs in more focused, restricted applications, such as "bite size artificial intelligence" that aimed to apply artificial intelligence software to several Air Force missions. Possible applications that RADC investigated were scheduling tactical air operations, exercises, and war gaming. The uses of simulation that modeled the software under various operational scenarios were also investigated.[11]

RADC also explored increasing the reliability of software. In 1983, the Center inaugurated the Software Technology for Adaptable Reliable Systems (STARS) that sought to develop tools for measuring computer software reliability. In 1987, RADC published the *Software Reliability Prediction and Estimation Guidebook* that identified variables affecting the reliability of 59 software systems. In still another effort called the Automated Measurement System (AMS), RADC provided the means to automate tasks associated with specifying software quality factors prior to development.[12]

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[9] For more on KNOBS, see Article, n.a., "Design of Knowledge-Based Systems with a Knowledge-Based Assistant," *The Guide to Computing Literature* (IEEE Transactions on Software Engineering, Special Issue on Artificial Intelligence in Software Applications), vol. 14, no. 12, Dec 1988, pp. 1771-1791, at http://portal.acm.org/citation.cfm?id=55175, as of 4 Nov 05.

[10] *HRL*, p. 125.

[11] *HRL*, p. 125-6.

[12] *HRL*, pp. 156-7.

Spacecraft Electrical Power

Electrical power systems for spacecraft had their humble beginnings in the simple magneto and spark plug ignition systems used by the Wright Brothers on their first airplane. Just as the first airplane electrical systems borrowed extensively from the automobile, spacecraft technology grew out of the systems and organizations supporting aircraft power. However, the unique requirements of the space environment and the absence of a large, continuously operating engine from which to draw motive force quickly led to the specialization of space power research. The Soviet launch of Sputnik in 1957 began the space race and had a profound impact on technology development in many areas. "Aircraft power" became "aerospace power" in 1958 when the Air Force reorganized its labs and formed an Aerospace Power Division. That group's mission was "to address the issue of how to generate and supply electrical power to flight vehicles operating in the environment of near-earth space."[1]

The technology available for such applications was primitive: Sputnik used a small silver-zinc battery to supply 1 watt of power to its transmitter over a period of three weeks. Months later, the United States launched its first satellite, Explorer I, with equally simple mercury-zinc batteries. That was followed by the Vanguard satellite, which had a considerably more sophisticated electrical system. It carried photovoltaic cells (for power needs while in the sunlight) coupled with rechargeable batteries (for operation in the dark) to power its transmitter and instruments. The power output was the same as for Sputnik, but the solar/battery combination allowed Vanguard to operate continuously in sunlight or darkness over a period of six years. These first satellites went into space more to prove it was possible than for practical purposes. That quickly changed, however, and both the payload and support systems of satellites grew

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[1] Paper, Lowell D. Massie, "A History of the Aerospace Power Division" [hereafter cited as "Aerospace Power Div"], 1 Sep 92, pp. 5-6.

in size and complexity, creating a demand for onboard electrical power systems. These systems brought with them a myriad of new requirements, depending on their missions: compact size, low weight, longevity, the ability to be recharged, high output, temperature insensitivity, and more. To meet these requirements, the engineers and scientists of the Aerospace Power Division began research programs in batteries, photo-galvanic and then photovoltaic cells, and fuel cells for all space applications. The origins of these three technologies predated the space age and can most directly be traced to the burgeoning of scientific research into electrical phenomena during the 19th Century.[2]

Simple batteries, for example, may have been devised by the ancient Egyptians, among others, but experienced a wave of development beginning in the late 1700s that resulted in modern battery technology. The first generations of aircraft used batteries for their ignition systems and to power other accessories. Even after the magneto came into popular use, batteries often remained on board for radio power or other devices. These basic lead-acid batteries were recharged between flights and remain a staple of automotive power today. However, the required upkeep and weight of a lead-acid battery prohibited its use on spacecraft. One of the critical parameters for satellite-borne batteries is energy density (watt-hours/kilogram), another area in which lead-acid batteries performed poorly. Satellite designers then turned to a somewhat newer technology, nickel-cadmium (NiCd) batteries. Later popularized as the most ubiquitous consumer rechargeable battery through the 1990s, NiCd batteries offered very consistent performance over their lifetimes and required little-to-no maintenance for continued operation. In the 1950s, the Aerospace Power Division's predecessor developed the first NiCd aircraft battery, and by 1966 produced the first maintenance-free version, built by Gulton. The Propulsion Lab also developed on-board charging systems for aircraft. However, the Luftwaffe

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[2]   Article, Anthony K. Hyder, "A Century of Aerospace Electrical Power Technology" [hereafter cited as "Aerospace Electrical Power"], *Journal of Propulsion and Power*, vol. 19, no. 6, Nov-Dec 03, pp. 1155-1165.

had used NiCd batteries during World War II, as much of the critical early technology was developed and patented in Germany during the 1920s and 1930s. As in other areas, the Allies took NiCd technology from the Germans and the U.S. Army used it during the Korean War. In 1959, Explorer 6 took the first NiCd batteries into space, marking the beginning of their status as the most-used satellite battery over the next several decades.[3]

In the mid-1960s, the Propulsion Laboratory conducted research efforts on hydrogen-oxygen fuel cells, which used catalytic hydrogen electrodes. Pairing that electrode with a nickel electrode in a battery configuration offered theoretical advantages in energy density, cycle life and depth-of-discharge. In 1971, Mr. Donald Warnock, of the Aerospace Power Division's Batteries and Fuel Cells Section, became aware of some preliminary commercial investigations being done in this area. Based on those initial discussions, he started a very small in-house nickel-hydrogen battery effort, which "met with immediate and exciting success." In September of 1972, he requested seed funds from the lab to expand the work and include contractors. With the director's approval, the money paid for the Air Force's first effort in nickel-hydrogen battery development. His in-house effort resulted in pioneering developments, particularly the configuration produced by Hughes Aircraft. A parallel effort by Intelsat concurrently pursued a different approach, which led both them and the Air Force to test their batteries on separate satellites. The Air Force's 21-cell, 50-amp-hour battery was built by the Eagle-Picher Company and was launched as an integrated experiment onboard a then-classified spacecraft in June 1977, the

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[3] "Aerospace Electrical Power," pp. 1172-1175; Manuscript, Dr. James F. Aldridge, ASC/HO, "USAF Research and Development" [hereafter cited as "R&D"], 1997, pp. 47-48; Paper, Aero Propulsion and Power Laboratory, "Biggies! 150 Biggests, Firsts, and Bests by the Aero Propulsion and Power Laboratory" [hereafter cited as "Biggies"], n.d. [ca. 1990]; Paper, Larry Howell and Paul Scardaville, "Nickel Cadmium Batteries in Aircraft Application," in *Proceedings of The IEEE Thirteenth Annual Battery Conference on Applications and Advances,* 13-16 January 1998, p. 75; Paper, Don Warnock, "Battery/Fuel Cell Technical Area" [hereafter cited as "Battery/Fuel"], Jun 87, p. 11.

same month as the Intelsat experiment. Both proved successful, leading to further development in industry and by the Air Force. The Propulsion Lab continued to provide critical research and pursue applications such that Nickel Hydrogen batteries based on their pioneering work are now the predominate power source for all military and civilian satellites, such as the Hubble Space Telescope.[4]

Fuel cells, which use the reaction of hydrogen and oxygen with a catalyst to produce water and electricity, were developed to a limited extent using a variety of electrodes and other components. The U.S. Army sponsored fuel cell research in the 1940s but this technology never found serious application through World War II. However, the diverse knowledge base created during that period, especially in Britain, "set the stage for a resurgence of interest in afterwards." Over the next two decades, the topic spread in the U.S. from the Army, the Navy, the Air Force, and its myriad contractors and academic researchers. By 1960, the Advanced Research Projects Agency latched on to fuel cells as a promising technology and sponsored research in the field at several institutions. The labs at Wright-Patterson were involved with the sponsorship of fuel cell research as early as 1959, specifically for spacecraft application. They contracted with General Electric and Pratt & Whitney, among others to develop this technology. One effort was the Hydrogen-Oxygen Primary Extraterrestrial (HOPE) fuel cell. This program advanced the state-of-the-art by creating a workable fuel cell, sending it into space atop a Blue Scout rocket, and obtaining data under actual operational conditions. The Air Force research

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[4]   Rpt, Don R. Warnock, "Advanced Nickel-Hydrogen Battery Technology," October 1977, pp. 1-9; "Aerospace Electrical Power," pp. 1173-1175; "Battery/Fuel," pp. 1-3; Paper, Lee Miller, "The Nickel-Hydrogen Battery System: An Historical Overview," in *Proceedings of the 16th Intersociety Energy Conversion Engineering Conference*, August 9-14, 1981, Atlanta, Georgia, vol. 1, pp. 220-222; Tech rpt, D. James Smith and Lee E. Miller, "Nickel-Hydrogen Battery Space Experiment," AFAPL-TR-78-43, Jul 78, pp. xi-xii, 1, and 205.

during the early 1960s emphasized alkali fuel cells, which generally employ compressed hydrogen and oxygen with a solution of potassium hydroxide in water as the electrolyte. This type is very efficient and produces potable water as a byproduct, but requires pure hydrogen and a platinum catalyst. The water production made them a natural choice for the new NASA manned space program and was strongly advocated by the Air Force. The long duration Gemini missions and the Apollo flights to the moon required electrical production over a period of two weeks and in the several kilowatt range, clearly outside the realm of battery power. Gemini proved the technology was viable for manned flights and every Apollo lunar mission used fuel cells derived from technology developed in part in the Aerospace Power Division. That organization continued to improve fuel cell designs for higher power density until the mid-1970s, but wanted for applications until the Strategic Defense Initiative reinvigorated the technology in the 1980s.[5]

Solar cells are also a technology older than the airplane. The phenomenon of photovoltaics was first observed in the 19th Century and the first solar cell was built in the latter part of that century. In 1941, the first silicon-based solar cell was devised and World War II provided the impetus behind further developments in semiconductor materials relevant to solar cells. It was not until 1954 that inventors at Bell Labs created a practical silicon solar cell, which was about 6 percent efficient and resulted in an immediate initiation of work in this area within the Aerospace Power Division. Five years later, the first satellite carried solar panels into space. The first generation of satellites used solar cells were spacecraft body-mounted. In 1966, the Aerospace Power Division started its

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[5] Article, Patrick G. Grimes, "Historical Pathways for Fuel Cells: The New Electric Century," *IEEE AES Systems Magazine* (Dec 00), pp. 8-10; Website, Smithsonian National Museum of American History, "Fuel Cells," available on the internet: http://americanhistory.si.edu/fuelcells/intro.htm, as of 22 Nov 05; Rpt, General Electric Co. Missile and Space Division, "Hydrogen-Oxygen Primary Extraterrestrial (HOPE) Fuel Cell," ASD-TR63-181, May 63; "R&D," p. 48; "Biggies"; "Battery/Fuel," p. 2.

Advanced Power Supply Technology program to combine recent advances in electrical components into Earth orbital demonstration systems. The lab started the then-secret Flexible Roll-Up Solar Array (FRUSA) project in 1966 under that program as a potentially more volumetrically efficient, pointable photovoltaic array. Previous solar arrays used blankets of photovoltaic cells rigidly attached to beams that were extended and fixed in place in order to operate in space. The flexible array developed by contractor Hughes instead rolled up like a blanket, allowing for storage prior to and during launch in a more compact space and thus a larger surface area in space. In October 1971, the lab-sponsored FRUSA power system launched into space aboard a Thor-Agena rocket, then deployed for a successful six-month flight test. The 5.5 by 32-foot array produced 1.5 kW of electricity for the Agena spacecraft and validated its sun acquisition and tracking mechanism and other components, as well as provided extensive data on the solar cells' performance. Aside from having direct application to the succeeding generation of military satellites, the flexible arrays transitioned to NASA for use on its ground-breaking Hubble Space Telescope. The lab followed this work with many critical developments in radiation hardening of solar cells and higher efficiency cells, particularly through the SDI program.[6]

The AFRL Propulsion Directorate and its predecessors contributed to or led the advancement of electrical power system technologies used on many military and civilian satellites to this day. The work of its scientists and engineers in batteries, fuel cells, and solar cells over the past fifty years touched on every aspect of power collection, generation, and storage that was critical to enabling satellites to carry ever more advanced capabilities. The funding provided in the aftermath of Sputnik in the 1960s and the Strategic Defense Initiative in the

[6]   "Aerospace Electrical Power," pp. 1167-1171; "Aerospace Power Div," pp. 8-14; "Biggies"; Tech rpt, Edward O. Felkel and George Wolff, "Flexible Rolled-Up Solar Array," AFAPL-TR-72-61, 30 Jun 72; Research summary, Lowell D. Massie, "Flexible Rolled-Up Solar Cell Array," 17 Sep 74.

1980s truly pushed revolutionary advancements in space power technologies. The legacy of that work remains in the AFRL Propulsion Directorate today and continues to influence the design of air and space power systems.

Spacecraft Electronic Component Radiation Hardening

Shortly after the United States successfully launched unmanned space satellites in the late 1950s, it was evident that electronic components were highly susceptible to the effects of natural radiation. Air Force laboratories conducted research into the effects of both natural radiation and those resulting from man-made high altitude nuclear detonations, and quickly determined that protecting a satellite's electronic systems from transient errors or permanent system failure is one of the essential requirements for successful space flight. Air Force scientists tested those components and developed passive countermeasures, using materials to shield the sensitive components or hardening the parts themselves. The greatest breakthroughs in this effort resulted in radiation-hardened space computers now used in essentially every military, government, or commercial spacecraft system operated by the United States.

Radiation emitted from solar flares and carried on the solar wind interacts with both spacecraft materials and electronics to cause degradation, upset, and systems failures. This damaging solar radiation exists as electromagnetic waves in the form of X-rays or gamma rays, and electrically charged electron, proton, or alpha particles. Transient single events occur when individual particles or x-rays pass through sensitive spacecraft instruments, sensors, or computer chips, generating false readings or other logical errors. Cosmic rays, which usually arrive from other galaxies, are of particular concern in causing transient upset. Prompt x- and gamma-rays resulting from nuclear explosions in space can cause either transient upset events in cables and circuits or catastrophic component failures. Of greatest concern are the Van Allen belts where most of the manned and unmanned spacecraft operate. These two electromagnetic donut-shaped rings trap and retain charged solar and cosmic particles. Long duration exposure to trapped radiation in the Van Allen belts can result in a significant accumulation of total ionizing radiation dosage and degrade electrical devices until they no

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longer function. Additionally, man-made detonations can significantly increase Van Allen belt radiation well above normal levels.[1]

The unique mission of Air Force space systems, such as surveillance and missile launch detection and interception, requires that spacecraft communication and navigation systems operate during and after a nuclear exchange as well as under normal circumstances. Because of this unique military requirement to survive nuclear detonations, Air Force laboratories placed added emphasis on man-made radiation, and how to counter those effects. Concerns about possible effects of a man-made nuclear blast emitting neutrons, gamma rays, and x-rays in the upper atmosphere, and how a blast would affect the Van Allen belts (discovered in 1958) and their impact on spacecraft systems, led to a series of space radiation experiments.[2]

In 1958, DoD's Argus program detonated three separate nuclear devices at 300 miles altitude over the South Atlantic Ocean, and four years later, the Starfish high altitude test occurred over Johnson Island in the Pacific. These detonations caused spacecraft electronic systems outages, and even entire satellite failures. The Air Force Special Weapons Center (AFSWC) and its descendent Air Force Weapons Laboratory (AFWL) measured and analyzed the radiation and its effects. The first spacecraft experiments with various levels of shielding to deflect radiation occurred in the fall of 1962. The results defined the levels of radiation that would cause major systems failures and prohibit manned

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[1] Book, Thomas D. Damon, *Introduction to Space: The Science of Spaceflight* (Malabar, Florida: Krieger Publishing Company), 1995, pp. 49-63; Briefing, N. Sramek, The Aerospace Corporation, "Radiation Hardened Electronics for Space Systems" [hereafter cited as "Radiation Hardened"], 12 June 2001, pp. 5-12; Notes/comments, Marion Schneider, AFRL/VSOP, "on Spacecraft Electronic Component Radiation Hardening draft," 10 Nov 2005.

[2] "Radiation Hardened, " p. 12; Schneider, notes/comments, 10 Nov 2005.

spaceflight, including high-altitude nuclear explosions that could disrupt satellites operating in low-earth orbit.[3]

Between 1959 and 1990, AFWL and the Air Force Geophysics Laboratory (AFGL) and their predecessors flew over 75 space missions to acquire information on space radiation, while rocket probes accumulated more data. In the 1960s, AFWL scientist Glenn Ainsworth, and Lieutenants Joe Janni and Marion Schneider developed passive and active dosimeters and particle spectrometers for use by space probes and NASA's Gemini astronauts to measure radiation and the value of shielding to protect space crews. AFGL and its predecessors and descendents developed sensors and computer software programs designed to predict space environments and their effect on spacecraft systems and electronics.[4]

Air Force labs developed a number of programs to counteract the effects of space radiation. About 1964, AFWL began developing radiation shielding codes to model spacecraft protection and transport prediction codes to calculate radiation levels for manned operations. By 1967, DoD concerns over space radiation resulted in the Joint Chiefs of Staff establishing a set of standard requirements for spacecraft system survivability. AFWL used these codes and criteria to conduct satellite vulnerability analysis through computer modeling to verify spacecraft designs with nuclear hardness specifications for a broad range of Air Force and DoD programs. Beginning about 1960, AFSWC's Transient Radiation Effects on Electronics Systems facility began to irradiate spacecraft

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[3] Paper, Marion Schneider, AFRL/VSOP, "Chronology of Programs and Milestone Accomplishments" [hereafter cited as "Chronology of Programs"], n.d.; Schneider, notes/comments, 10 Nov 2005; Rpt, Defense Nuclear Agency, "Operation ARGUS, 1958," DNA 6039F, April 1982, p. 1.

[4] "Chronology of Programs;" Paper, Ruth P. Liebowitz, ESC/HO, "Air Force Geophysics, 1945-1995: Contributions to Defense and to the Nation," April 1996, pp. 35-40; History, AFWL/HO, "History of the Air Force Weapons Laboratory, 1 January – 31 December 1966," 1967, pp. 340-368.

electronic components, testing them for vulnerability to both natural and man-made radiation. These studies, focused on such military systems as the Minuteman missile program, the Manned Orbiting Laboratory, Defense Support Program, the U.S. Navy's Fleet Satellite Communications program (FLTSATCOM), the Military Strategic Tactical and Relay (MILSTAR) program, Defense Meteorological Support Program, and Global Positioning System satellites, continued into the 1990s. For example, after Defense Support Program satellites incurred outages due to a 1972 solar flare, the program routinely had AFWL test their electronic components. In 1981-82, AFWL tested systems components for FLTSATCOM to ensure communications survivability during a nuclear exchange. And in 1987, AFGL's Combined Release Radiations Effects Satellite or CRRES quantified radiation effects on 65 different components used in space. During this period, AFWL also evaluated ground-based facilities requiring protection from high altitude nuclear-generated electromagnetic pulse (EMP).[5]

With the advent of silicon wafer scale technology used in computer circuit boards, replacing older transistor-based systems, the Air Force began to evaluate ways that the circuit board might be hardened to resist radiation effects. Beginning in 1974, the Air Force Space and Missiles Systems Organization (SAMSO) needed space-qualified memory circuit boards for its systems and tapped Captain Marion Schneider, a recent transfer from AFWL, for this task. Working with Air Force Materials Laboratory and Air Force Weapons Laboratory, SAMSO developed a family of hardened memory chips. Air Force labs worked with RCA Corporation in making the radiation hardened Complementary Metal

[5] "Chronology of Programs;" Schneider, notes/comments, 10 Nov 2005; E-mail, Marion Schneider, AFRL/VSOP, to Stephen Watson, AFRL/VSIH, "Telsat Space Radiation Briefing," Oct 26, 2005; Paper, Neal Peck, AFRL/VSO, "Air Force Research Laboratory Space Vehicles Directorate Contributions to Key Air Force Capabilities" [hereafter cited as "Air Force Research Laboratory"], Dec 1999; History, AFSTC/HO, "History of the Headquarters, Air Force Space Technology Center, 1 October 1983 – 30 September 1985" [hereafter cited as "History-AFSTC"], vol. I, 1986, pp. 157-160.

Oxide Semiconductor (CMOS) RCA 4000 series used for SAMSO's spacecraft systems, while NASA and commercial satellites also benefited from this Air Force effort.[6]

Under the auspices of the Air Force Space Technology Center (AFSTC), a number of programs designed to harden space electronics such as memory chips and processors took shape. The 1984 Military Space System Technology Plan (MSSTP) indicated the future need for total satellite memory in the 500 Megabit range, but current hardened chips had only 4,000 (4K) bits of memory. AFSTC, working through Sandia National Laboratory, developed a hardened 16K bit chip, then a 64K bit chip, and moved toward a 256K hardened chip. The MSSTP also outlined requirements for smaller, faster, lighter, reliable, low-powered hardened processors. AFSTC turned to a new technology already recognized by DoD called Very High Speed Integrated Circuits or VHSIC. VHSIC promised a quantum leap in performance, as one VHSIC chip could do the work of numerous older chips. AFSTC abandoned both projects in 1984 due to a lack of customers for the memory chip and lack of contractors to develop the VHSIC processor. But the promise of these technologies was too great to abandon altogether.[7]

Building on VHSIC's foundation, AFSTC began the Generic VHSIC Space Computer or GVSC program. The GVSC program's goal was to develop a radiation-hardened Military Standard 1750A VHSIC processor chip, designed generically for use across a wide range of satellite programs, as opposed to building chips for each program. Program manager Russ Herndon designed GVSC as a two-phase risk reduction effort. First, in July 1985, AFSTC contracted with four companies—Harris, Honeywell, IBM, and RCA—to develop VHSIC chip sets that were not designed as prototypes, but rather that contained

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6   "Chronology of Programs;" Schneider, notes/comments, 10 Nov 2005.

7   "History-AFSTC," pp. 144-148, 150-153.

basic processor components. Having all four contractors working on the chips would demonstrate their mastery of VHSIC technologies and prove that they could reliably produce the chips in quantity. Once completed in 1987, the government determined that the chips met or exceeded AFSTC radiation hardness goals.[8]

GSVC phase-two contracts, covering design, production, and testing of space-qualified VHSIC breadboard chip sets, went to Honeywell and IBM. By having two suppliers, AFSTC hedged its bet in case one contractor failed, and could point to successes by one if the other faltered. To minimize costs, AFSTC reduced the project's scope and set aside some technical aspects to restore later. The success of this approach was proven when the contractors sent chipsets a year ahead of schedule. Certification testing found that both contractors' devices had met or exceeded protection goals. The flow of deliverables started in March 1989, and intense customer demand immediately followed. The GVSC program was the first to demonstrate that a VHSIC-level bulk CMOS fabrication process could be hardened to military space levels. AFSTC's descendent Phillips Laboratory first used the GVSC successfully on the autonomous navigation system aboard its Technology for Autonomous Operational Survivability (TAOS) satellite, launched in March 1994.[9]

[8]   "History-AFSTC," pp. 154-156; History, AFSTC/HO, "History of the Headquarters Air Force Space Technology Center, 1 October 1985 – 30 September 1987," vol. 1, 1988, pp. 162-164; History, AFSTC/HO, "History of the Headquarters Air Force Space Technology Center, 1 October 1987 – 30 September 1989" [hereafter cited as "History-AFSTC, 1987-1989"], vol. 1, 1990, pp. 180-181.

[9]   "History-AFSTC, 1987-1989," pp. 180-184; History, PL/HO, "History of the Phillips Laboratory, 1 October 1991 – 30 September 1992" [hereafter cited as "PL History"], vol. 1, pp. 123-126; E-mail, Dr. Creigh B. Gordon, AFRL/VSSE, to Stephen Watson, AFRL/VSIH, "Historical Significance of the VHSIC and GVSC Programs" [hereafter cited as "Historical Significance"], 31 Oct 2000.

Some electronic devices could not be sufficiently hardened. Beginning in 1979, AFWL scientists studied the concept that shielding of individual packages would be superior to conventional shielding at the box, board, or system levels. Using improved package designs and production techniques as well as new materials, such as lightweight integral tungsten, these "Rad-Paks" provided a 300-fold reduction in total radiation dosage and a 65 to 85 percent weight savings. Although Rad-Paks would not protect circuits against all radiation, they provided protection against both total ionizing dosage as well as transient X-rays. When AFWL testing indicated the vulnerability of certain insufficiently hardened components aboard Global Positioning System (GPS) Block II satellites built in 1983-84, Rad-Paks were used to protect those GPS electronic systems. AFGL included Rad-Pak shielding in its CRRES satellite launched in 1987. Rad-Paks soon became available for non-hardened commercial satellite systems.[10]

Emulating the successes of GVSC, AFSTC established the follow-on, two-phased Advanced Spaceborne Computer Module (ASCM) program. ASCM's first phase meant using GVSC technology to build the entire computer under Military Standard 1750A architecture. ASCM would be a standardized computer, but its modular components would build in flexibility and adaptability for future systems. Like GVCS, ASCM's potential attracted customer interest and funding. ASCM contracts called for production innovations to enhance productivity. Two competing contractors used the same design language and exchanged subassemblies that worked in the other's device. Rather than test every part at the end of the assembly process, AFSTC's contractors built "test characterization vehicles" into the wafers so they would be evaluated during assembly. Using the accumulation of data, the entire "Qualified Manufacturing Line" could be certified as building space-qualified parts. AFSTC let its phase-one contracts in October 1989 to Honeywell and IBM Federal Systems (which later became Lockheed

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[10] Paper, Peck, "Air Force Research Laboratory," Dec 1999; "History-AFSTC," pp. 160-161.

Martin Federal Systems). Honeywell delivered its 16-bit Control Processor Module (CPM) to AFSTC's descendent Phillips Laboratory in December 1991, and Lockheed Martin delivered the following year. A Phillips Lab CPM was flight proven aboard the Clementine satellite, and in 1997, the lab used the 1750A CPM for NASA's Cassini spacecraft.[11]

Using these two contractors, ASCM's second phase Advanced Technology Insertion Module (ATIM) program moved beyond the 1750A to design and fabricate 32-bit integrated circuit computers required to meet high performance, space-qualified, low power, and low cost, control and data processing needs. Lockheed Martin quickly developed the radiation hardened Reduced Instruction Set Computing (RISC) 32-bit computer. Phillips Laboratory provided an ATIM RAD6000 processor to NASA for use in the Mars Pathfinder Rover, launched in 1996. More than 40 Air Force, DoD, NASA, and commercial systems, and more than 90 percent of satellites launched today, use ATIM technology.[12]

In 1998, Air Force Research Laboratory's (AFRL) Space Vehicles Directorate started a program based on PowerPC architecture. Radiation hardened PowerPC microprocessors utilize standard interfaces and run commercial software, making application development simpler and more affordable for satellite builders. Competing contractors Honeywell and BAE Systems produced and verified these devices in the next two years, and they have been delivered to flight programs including XSS-11, MILSATCOM, and

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[11] "History-AFSTC, 1987-1989," pp. 185-188; "PL History," pp. 176-180; Briefing, Capt Ron Marx, PL/VTEE, "Advanced Technology Insertion Module (ATIM)," 14 Dec 1994; "Historical Significance."

[12] "Chronology of Programs;" "PL History," pp. 176-180; History, PL/HO, "Close-out History of the Phillips Laboratory, 1 October 1996 – 30 October 1997," vol. I, 1998, pp. 656-658.

GPS-III. BAE Systems utilized next-generation Hardening By Design tools and techniques to further improve and make affordable higher performing spaceborne electronics.[13]

AFWL also developed advanced microelectronic packaging technology in the form of High Density Interconnect (HDI) that reduced component size and weight to improve speed, performance, survivability, and reliability. Later, Phillips Lab built the advanced packaging, high-density Multi-Chip Module or MCM. HDI technology has emerged as the leading advanced packaging approach for multi-chip modules, sensor-electronics integration, and system-on-a-chip for small satellite concepts.[14]

AFSTC did not abandon its work on memory chips for space systems. The same AFSTC contractors working on GVSC technology worked in parallel on the 64K SRAM. Working with AFWL, AFSTC produced a 256K Static Random Access Memory (SRAM) device based on VHSIC technology. These memory devices provided an unprecedented level of performance and reliability for nearly every space system built in the late 1990s. Then in early 2000, AFRL initiated development of a fast, hardened, reliably manufactured nonvolatile or NV

[13] Notes/comments, Ken Hunt, AFRL/VSSE, "on Spacecraft Electronic Component Radiation Hardening draft," 14 Nov 2005; Article, AFRL/XPTC, "Tab—2 Emerging Technologies: PowerPC for Space," *Air Force Research Laboratory Success Stories, A Review of 2001*, 2002, p.56; Article, AFRL/XPTC, "Tab—2 Emerging Technologies: PowerPC Processors Fly on Air Force Missions," *Air Force Research Laboratory Success Stories, A Review of 2000*, 2001, p.73.

[14] Hunt, notes/comments, 14 Nov 2005; Article, n.a., "Three-Dimensional Advanced Multi-Chip Module (MCM) Technology," *Phillips Laboratory Success Stories 1993-1994*, 1995, p. 73; Article, n.a., "Award for Excellence in Technology Transfer in Advanced Microelectronics Packaging," *Phillips Laboratory Success Stories 1993-1994*, 1995, p. 83.

memory chip at BAE Systems that yielded the first hardened 4MB NVRAM for space use.[15]

From the inception of space flight, the Air Force laboratory system has addressed the essential need to protect against the harmful effects of natural and man-made space radiation that can cause temporary or permanent failure in space electronics systems. Developing passive shielding and radiation-hardened components, Air Force scientists leveraged their prior successes to advance and improve succeeding generations of shielding, memory chips, and integrated circuit processors. In addition, Air Force labs pioneered standardized techniques for chip design, fabrication, and mission qualification. The Air Force labs have provided key assistance to military satellite programs in every arena: modeling and design, testing components, implementing shielding or hardened parts, and integrating advanced microelectronic packaging, all of which have saved spacecraft users time and expense while assuring a satellite's operational integrity to successfully meet combat support missions. All U.S. military spacecraft, including GPS and MILSTAR, the Minuteman III missile upgrade, and virtually all commercial and government and NASA spacecraft, use these AFRL-legacy devices.

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[15]   Hunt, notes/comments, 14 Nov 2005; Article, n.a., "High Capacity Spaceborne Memory Modules," *Phillips Laboratory Success Stories 1993-1994*, 1995, p.93.

Synthetic Aperture Radar (SAR)

Militaries of the world have been trying to penetrate the "fog of war" long before the term was attributed to 19th century military theorist Carl von Clausewitz.[1] While Clausewitz spoke metaphorically of the confusion and chaos that invests every military campaign and battlefield, more often than not commanders on the ground (or in the air) have had in mind more tangible impediments to vision. Indeed, one of the major technological hurdles challenging airpower advocates for much of the 20th century was how to see through weather, fog—and camouflage—in order to target and destroy elements of an enemy's war making capability.

It was not until the emergence of effective radar in the second quarter of the 20th century that this goal began to be realized. However, it would take several more decades until all the critical elements of what is today known as synthetic aperture radar came together for effective military (and subsequently, civilian) use. The organization responsible for developing the initial concepts and subsequently promoting and financially underwriting the development of SAR has been the Sensors Directorate of the Air Force Research Laboratory (AFRL/SN) and its predecessor organizations at Wright Field, Dayton, Ohio, principally the Air Force Avionics Laboratory (AFAL).[2]

SAR is the means by which an airborne antenna—commonly a phased array—is used to simulate a much larger antenna by collecting radar data as the

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[1]   Article, Maj (NS) Chia Eng Seng Aaron, "Countering the Friction and Fog of War in the Information Age," *Journal of the Singapore Armed Forces* (Apr – Jun 2003), at www.minddef.gov.sg/safti/pointerback/journals/2003/Vol29_2/6.htm, as of 29 Nov 05, p. 1.

[2]   The Air Force Avionics Laboratory was established in 1963 by combining several smaller laboratories of the erstwhile Wright Air Development Division. See Study, Dr. James F. Aldridge, ASC/HO, "A Historical Overview of the Mission and Organization of the Wright Laboratory, 1917-1993," Nov 1994, pp. 16-17.

aircraft moves forward and then processes the information as if it came from an antenna several hundred meters long. The development of SAR technology in the half century after World War II resulted in increased radar resolution and the ability to detect objects and targets of military interest through clouds, foliage, camouflage, and even the surface of the earth that would otherwise remain hidden to other forms of visual, infrared, or hyperspectral sensor reconnaissance.[3] Next to stealth technology—and the invention of radar itself— SAR is probably the most remarkable development in military sensor technology in the 20th century.

The concept of SAR was first broached by Carl Wiley at Wright Field in the late 1940s. Wright Field sponsorship of SAR research was continued by Wiley and William R. Boario in 1950s. The Avionics Laboratory underwrote research at Willow Run Laboratories at University of Michigan and its successor, the Environmental Research Institute of Michigan (ERIM), beginning in the 1960s.[4]

A primitive form of SAR, called Doppler Beam Shaping (DBS), was first advanced by Wiley and Boario and demonstrated at the University of Illinois. It was an "unfocused SAR." Focused SAR was first demonstrated at Michigan's Willow Run Labs, in 1957. This was a side-looking SAR with a resolution of around 100 feet in range and azimuth, at ranges of tens of miles.[5]

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[3]   Intvw, Floyd P. Johnson, AFRL/SNZ, with Dr. James F. Aldridge, AFRL/HO, 23 Nov 05.

[4]   Article, William M. Brown, Jack L. Warner, and William R. Boario, "Sighted Automation and Fine Resolution Imaging," *IEEE Transactions on Aerospace and Electronic Systems* [hereafter cited as *IEEE Transactions*], vol. 40, no. 4, Oct 04, p. 1423.

[5]   This research was sponsored by the U.S. Army. See *IEEE Transactions*, p. 1424.

In the 1960s there appeared the first experimental examples of SAR technology for weapons application. These included the APO-109, an early optically processed SAR; the Hi Gasser, an early investigation of autofocus; SARCALM or SAR Command Air Launched Cruise Missile; SARG (or SAR Guidance), an early study of the use of SAR for weapons guidance using Doppler foldover phenomena; FOPEN, an early investigation of foliage penetration by SAR; Project RAIN, or Radar Aided Inertial Navigation; and Polyfreq, or the first real wide band SAR. The IMFRAD was a foliage penetration SAR that was installed on a C-141 aircraft during the decade.[6]

In the 1970s the maturation of digital technologies affected the development of SAR-based systems, making possible, among other things, the first real-time processing of SAR images.[7] Capabilities and technical developments that benefited from these and/or other advances and technical refinements included FLAMR, or Forward Looking Advanced Multi-Mode Radar; LCAR, or Low Cost Attack Radar; IMFRAD, a VHR SAR for FOPEN measurements; Spotlight & Poly frequency, for UHR SAR testbeds; Pave Mover, an integrated slow ground moving target indicator (GMTI) and SAR testbed; CORSI, or Coherent Radar Seeker Investigation, and EAR, the Electronically Agile Radar for the B-1 bomber.[8]

The 1980s witnessed the development of even more capable SAR-based sensor applications. These included: EMRT, or Electronic Multi-Function Radar

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[6]   Briefing, Floyd "Paul" Johnson, AFRL/SNZ, "Synthetic Aperture Radar (SAR) Heritage: An Air Force Perspective," 49th Annual Tri-Service Radar Symposium, Boulder, Colorado, 23-27 Jun 03, n.d.; Chart, AFRL/SN, "Synthetic Aperture Radar Technology" [hereafter cited as "SAR Technology"], n.d.; and Chart, AFRL/SN, "Synthetic Aperture Radar Technology S&T Investment" [hereafter cited as "SAR S&T Investment"], n.d.

[7]   Intvw, Johnson with Aldridge.

[8]   "SAR Technology"; "SAR S&T Investment."

Technology with electronic counter-counter measures (ECCM); the Ultra Reliable Radar (URR) testbed for the F-22; SASSI, or Synthetic Aperture Seeker System Investigation; ASARG, or Advanced SAR Guidance; SIR-B, or Shuttle Imaging Radar Bistatic Experiment from Space; the T-Bird, or Tactical Bistatic Radar Demonstration (a multi-mode bistatic SAR); and bistatic SAR systems studies conducted under the name Covert Strike.[9]

The 1990s saw greater refinements in SAR technologies. Thus there was FOPEN SAR, a second generation FOPEN incorporating three decades of advanced processing, antenna technology, and radio frequency (RF) devices; RADCON that developed algorithms for detecting concealed targets; IPSART, which integrated precision SAR targeting; ARAGTAP, an automatic radar air-to-ground target acquisition program; the Moving and Stationary Target Acquisition and Recognition (MSTAR) program; and Hammerhead, a third generation SAR Guidance system.[10]

Initial military use of SAR technology was for surveillance and reconnaissance of strategically important military targets, like ballistic missile silos.[11] Indeed, one of the principal motivations of early SAR pioneers was to develop a more precise means of locating and precisely hitting enemy targets in order to make Mutually Assured Destruction (MAD) unnecessary in any future conflict between nuclear superpowers. Thus the RF-4, the SR-71 and the U-2 were all equipped with SAR capability.[12] With the development of real time imaging, starting in the mid 1970s, however, SAR began to be applied to tactical battlefield uses as well. Over time the F-15E, F-16, F-18, B-1B, B-2, F-22 and

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[9]   *Ibid.*

[10]   *Ibid.*

[11]   Intvw, Johnson with Aldridge.

[12]   *Ibid.*

Joint Direct Attack Munition (JDAM) all benefited from SAR targeting, as would the F-35 Joint Strike Fighter.[13] As the 20th century drew to a close, the SAR-equipped E-8A Joint Surveillance Target Attack Radar System (JSTARS) became an indispensable part of battlespace in every war fought by the United States from Desert Storm (1991) though Operation Iraqi Freedom (2004). (See separate paper on JSTARS.)

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[13] "SAR Technology."

Terrestrial Weather Forecasting

Becoming an all-weather flying force was one of the earliest goals of the post-World War II Air Force. While improving the quality of weather forecasting had been of great interest during the war, new technologies needed substantial advances. Recently invented jet engines meant acquiring a better understanding of weather patterns and atmospheric turbulence at higher altitudes, and within a few years, aerial refueling of bombers carrying nuclear warheads required more stringent forecasting requirements for this tricky and demanding operation. Consequently, the Air Force Cambridge Field Station's Geophysics Research Directorate (GRD), renamed the Air Force Cambridge Research Laboratories (AFCRL) in 1949, made meteorological studies and particularly weather forecasting a high priority. GRD and its descendents have made significant contributions to the defense community in two broad technical areas: first in forecasting the earth's terrestrial operational environment, and second in resolving atmospheric issues for military detection and targeting systems. In turn, this has meant efforts in three major areas of research: weather prediction, weather radar, and satellite meteorology. Although much of the early work was accomplished in the 1950s and 1960s, laboratory scientists continued to advance the study of the atmospheric sciences and produced remarkable benefits for both the military and civilian sectors.

GRD made an early contribution to terrestrial weather forecasting through the continued and expanding support of postwar academic meteorological research. While wartime research in meteorology and the atmospheric sciences had been contracted through five universities – University of California at Los Angeles (UCLA), California Institute of Technology (Cal Tech), University of Chicago, Massachusetts Institute of Technology, and New York University – by 1948, this group included the University of Alaska, Columbia University, Princeton University, the University of Florida, the Johns Hopkins University, the University of New Mexico, Penn State, and Stanford University. To disseminate

this academic research, in 1950 AFCRL contracted with the American Meteorological Society (AMS) to publish a new series of "Meteorological Abstracts." The following year, the lab also had AMS publish a new reference volume, the "Compendium of Meteorology." And in 1959, the lab's next iteration, Air Force Cambridge Research Center (AFCRC), co-sponsored and assisted in the preparation of the widely used handbook "Glossary of Meteorology."[1]

Before the end of World War II, weather forecasting was a subjective art, based primarily on surface observations supplemented by a very limited number of upper air soundings. Forecasting extreme weather events was incomplete beyond twelve hours. In the late 1940s, several events coincided to usher in a revolution in weather prediction that has greatly benefited mankind. First, the use of more and better balloon-borne meteorological instruments called rawinsondes significantly enhanced the world-wide network for upper atmospheric observation. Second, the theoretical basis for mathematically predicting future atmospheric conditions was established. And third, the invention of the electronic computer permitted the rapid capture of data and equally rapid calculations for weather forecasting.[2]

Numerical weather prediction (NWP) is the basis from which all weather forecast guidance is derived. NWP requires taking a world-wide network of meteorological observations, then producing complex mathematical models of the atmosphere on state-of-the-art mainframe computers. GRD, along with the Office of Naval Research, played a major role in developing the first numerical weather prediction techniques by underwriting a project led by John von

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[1]   Paper, Ruth P. Liebowitz, "Air Force Geophysics, 1945 – 1995: Contributions to Defense and to the Nation" [hereafter cited as "Air Force Geophysics"], April 1996, pp. 17-18.

[2]   Notes/comments, Donald Norquist, AFRL/VSBYA, "On Terrestrial Weather Forecasting," 28 July 2005.

Neumann at Princeton's Institute for Advanced Study. Air Force Captain Philip D. Thompson, who served at GRD and its descendent AFCRL from 1948 to 1954, worked with the Princeton group as project officer for the Electronic Computer Project. Thompson, instrumental in producing the first NWP model forecast using an electronic computer, also facilitated the project by bringing scientists Jule Charney and Arnt Eliassen aboard. Later, as head of the Numerical Prediction Project at AFCRL, Thompson led an effort to systematically evaluate the performance of the most promising newly developed NWP models using lengthier global meteorological observations. In 1952, AFCRL's Atmospheric Analysis Lab announced the production of upper-level wind forecasts in real time through numerical methods. Success in this endeavor led to the formation of an operational Joint Numerical Weather Prediction Unit made up of the Air Force, Navy, and U.S. Weather Bureau in 1954. In 1961, Thompson published "Numerical Weather Analysis and Prediction," a landmark text in the atmospheric sciences for over two decades. Later work carried on by the lab's Ralph Shapiro improved these NWP methods, and transferred the results to the National Weather Service.[3]

Weather radar signifies the application of radar techniques to the detection, analysis, and forecasting of meteorological phenomena, particularly hazardous weather conditions such as severe storms, tornadoes, and hurricanes. During World War II, radar's potential for weather applications became quickly apparent to military meteorologists. In 1941, the British used radar to track a rain shower over the English Channel. And by 1943, the U.S. Army Air Forces applied radar systems intended for harbor and air defense to observe weather conditions. Following the war, American military and civilian weather agencies jointly undertook Project Thunderstorm, a major program designed to analyze this weather hazard and to explore the use of radar and other techniques to detect such storms. In 1948, GRD established the Weather Radar Branch under its

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[3]   "Air Force Geophysics," pp. 18-19; Norquist, notes/comments, 28 July 2005.

Ionospheric Laboratory. Headed by David Atlas, a wartime weather officer and radar expert who had later participated in Project Thunderstorm, this group made what has been generally recognized as pioneering advances in the area of weather radar. Initially, these scientists observed the constituents and structure of precipitation, as well as explored the puzzling issue of radar backscatter echoes which occurred in a visually clear atmosphere. A controversial topic for more than a decade, by the late 1960s the lab used radar and airborne measurements to determine that turbulence, not "point targets" such as birds and insects, created these echoes.[4]

During the 1960s, Atlas's group focused on developing radar, especially Doppler radar, and its techniques to detect features of severe storms. Atlas and Roger Lhermitte developed a method to obtain the vertical profile of the horizontal wind vector from an azimuthally scanning Doppler radar, and in 1961 made the first measurement of a wind profile through this technique. In 1963, they received a patent for the technique, now known as Velocity-Azimuth Display or VAD. A member of the branch, Edwin Kessler, later transferred this lab-developed expertise to the National Severe Storms Laboratory, established at Norman, Oklahoma in 1964, when he became that lab's first director.[5]

In the era before digital color displays, AFCRL scientists and engineers developed the Plan-Shear Indicator (PSI) display for Doppler radar data. The PSI display consisted of concentric rings that were modulated in brightness in proportion to the reflectivity at each range, modulated in width in proportion to the Doppler spectrum width, and displaced radially on the display in proportion to the radial or Doppler velocity. In 1968, AFCRL's Ralph Donaldson used this display to become the first scientist to identify the wind circulation rotating aloft in a thunderstorm. This condition, known as a mesocyclone, is typically a precursor

[4]   "Air Force Geophysics," pp. 19-20; Norquist, notes/comments, 28 July 2005.

[5]   "Air Force Geophysics," p. 20; Norquist, notes/comments, 28 July 2005.

of a tornado. Also during the 1960s and 1970s, this group adapted Bell Laboratory's "pulse pair" signal processing technique to compute the Doppler mean velocity in storms at all sample ranges in real time. This capability is essential in understanding air motion within storms and wind-related weather hazards. The group also developed procedures for automated real-time analysis together with computerized displays of Doppler radar data.[6]

Building on this work, by the end of the 1970s AFCRL and AFGL participated in the Joint Doppler Operational Project in Oklahoma. Doppler radar had previously proven valuable in weather research, but had been viewed as impractical in weather prediction observations because of the perceived need to use at least two Doppler radars to measure the vector wind field in storms. The lab's demonstrated use of a single Doppler radar to provide operationally valuable information became the cornerstone of the Next-Generation Weather Radar (NEXRAD) Program. Sponsored jointly by the Departments of Defense, Transportation, and Commerce, this program developed the WSR-88D weather surveillance radar system for the National Weather Service, Air Force Weather Agency, and Federal Aviation Administration. WSR-88D consists of a Doppler radar, signal processor, and a radar product generator and incorporates a set of meteorological algorithms -- arithmetical problem solving procedures. AFCRL scientists developed nine of the system's nineteen algorithms, including storm tracking, storm position forecasting, hail detection, tornado detection, and VAD wind profiling. Deployed nationwide, NEXRAD replaced existing weather radar surveillance systems using 1950s technology, which only measured a storm's reflectivity and used little to no automated data processing. Later, the lab transitioned a mesocyclone-detection algorithm into the system, which detects severe rotation in thunderstorms in order to provide an assessment of the likelihood and probable intensity of tornadoes. Taken together, these Air Force laboratory-generated radar advances served to make Doppler weather usable for

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[6]   *Ibid.*

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everyday weather observation and forecasting, as well as aiding in the protection of Air Force assets in the so-called "Tornado Alley" of the Midwest, Southeast, and Southwest.[7]

Air Force scientists also contributed to the creation and use of satellite meteorology. Even before the first U.S. meteorological satellite, Tiros I, was launched, the lab sponsored Project Satellite Cloud Photo to evaluate the potential meteorological utility of televised images from a satellite vehicle and then to apply that information. In the late 1950s, AFCRC scientists Arnold Glaser and John Conover devised a method for using a camera system borne by a ballistic missile launched from the Eastern Test Range at Cape Canaveral. Following separation from the satellite, the camera capsule descended on a parachute while photographing clouds below. After retrieving the film from the Atlantic Ocean, the scientists used the photos to duplicate a satellite's geometry. AFCRL personnel helped to create the first satellite-derived analysis of cloud cover, using data from Tiros I in 1960. By 1962, AFCRL was one of the few locations in the world receiving a direct readout of meteorological satellite data. The recently formed space agency, NASA, took primary responsibility for the satellites and the U.S. Weather Bureau administered the use of the data for weather forecasting, but the lab contributed greatly to establishing the methodology for satellite meteorology.[8]

Beginning later in the 1960s, the lab began to assist the Defense Meteorological Satellite Program (DMSP). Initially a classified program, DMSP used cloud studies to aid with operations in the Vietnam War. Following its declassification in 1973, scientists from AFCRL and later the Air Force Geophysics Laboratory (AFGL) and its follow-on Phillips Laboratory improved satellite meteorological instrumentation, such as the microwave temperature and

[7]   "Air Force Geophysics," p. 21; Norquist, notes/comments, 28 July 2005.

[8]   "Air Force Geophysics," p. 22; Norquist, notes/comments, 28 July 2005.

moisture sounding sensors, which are still flown on DMSP satellites. Additionally, the lab developed cloud modeling techniques that included computer models for a more timely and accurate assessment of global cloud cover. These techniques utilized algorithms used for DMSP imagery, central to operational cloud analysis procedures in the 1970s and 1980s. In the mid-1990s, the lab developed other algorithms to integrate polar and geostationary satellite imagery at hourly intervals, providing cloud amounts in total and by layer, cloud top heights, and cloud types. This technique has permitted a more comprehensive spatial and temporal global analysis product which the Air Force Weather Agency now generates routinely.[9]

During the 1980s, the lab began to package its accumulated forecasting expertise for tactical military applications. A new program, called Tactical Decision Aids (TDA), combined weather data and forecasts with optical codes in software to maximize the performance of precision-guided munitions used in European tactical operations. By combining data on upcoming meteorological and optical background scene conditions with sensor models, TDAs predicted the relative performance of various electro-optical sensors used with munitions. This program helped mission planners to choose the most effective weapons for a given combat mission, and enable pilots to calculate acquisition and lock-on range for selected targets. By the early 1990s, weather support units made operational use of the fully developed version of this software, now termed Electro-Optical TDA (EOTDA).[10]

Due to the necessity of its military mission, Air Force laboratories have been pioneers in the use of terrestrial weather forecasting. In developing techniques and methods in numerical weather prediction, weather radar, and satellite meteorology, lab scientists have resolved atmospheric issues for detection and

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[9]   "Air Force Geophysics," pp. 22-23; Norquist notes/comments 28 July 2005.

[10]   "Air Force Geophysics," p. 23; Norquist, notes/comments 28 July 2005.

targeting systems that impact nearly every aspect of military operations, from intelligence and surveillance activities to theater and global missions. But in developing those important databases, software models, and Doppler radar weather systems, Air Force labs have become major partners with U.S. government weather agencies in predicting turbulent weather patterns that not only impact military assets, but have enhanced and improved the lives of ordinary American citizens.

Weapons Guidance Technologies

Finding more precise ways to put a bomb on target has been a main objective of the Air Force Research Laboratory's Sensors Directorate (AFRL/SN) and Munitions Directorate (AFRL/MN) and their predecessor organizations since World War I. In the 1920s and 1930s McCook and Wright fields' Armament Laboratory developed better bomb racks and during World War II fitted the Norden bomb sight to Air Force bombers.[1] The development of cruise and ballistic missiles during World War II, first by Germany and following the war by the U.S. and Soviet Union, increased the urgency of developing effective guidance systems; and the rise of advanced electronic technologies after the war provided the means to do this.   Three types of guidance technology were called for: standoff targeting, precise long-range navigation, and autonomous target acquisition.[2]

In the late 1940s, the Air Materiel Command (AMC) sponsored development of the Automatic Terrain Recognition and Navigation (ATRAN) guidance system that, in the 1950s, was fitted to the Air Force's *Mace* and *Matador* cruise missiles. ATRAN matched synthetic radar reference maps to the guidance system's radar images to provide a continuous area recognition and tracking system along the missile's pre-planned flight path.[3]

In 1955, the Air Force broke up Wright Field's Armament Laboratory. Munitions work and assigned personnel were transferred to Eglin Air Force Base,

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[1]   Article, n.a., "Welcome to the Norden Bombsight Web Page," n.d., at www.twinbeech.com/norden_bombsight.htm, as of 5 Dec 05.

[2]   Report, Dr. James F. Aldridge, ed., ASC/HO, "USAF Research and Development: The Legacy of the Wright Laboratory Science and Engineering Community, 1917-1997" [hereafter cited as "USAF R&D"], n.d., p. 89.

[3]   *Ibid.*

Florida, while at Wright Field, guidance work became part of a new laboratory, the Weapons Guidance Laboratory. Between 1959 and 1963, the Weapons Guidance Laboratory was integrated into the new Air Force Avionics Laboratory (AFAL).[4]

In 1959, the Air Force initiated development of the Terrain Contour Matching (TERCOM) system that continued through the 1960s and 1970s. The TERCOM system matched a pre-stored profile of terrain altitude with returns from the missile's radar altimeter. It was ideally suited for smaller, low-flying cruise missiles. In 1975, the Department of Defense (DOD) chose TERCOM for the Navy Tomahawk and Air Force Air Launched Cruise Missile (ALCM) and later for the Air Force's Advanced Cruise Missile (ACM) program.[5]

Meanwhile, the laser was invented in 1960,[6] and during the ensuing decade the Avionics Laboratory initiated research supporting the development of laser target designation systems and laser guided bomb units. In 1964, the Air Force demonstrated a laser targeting system at Eglin AFB, and in 1965 began work on an Airborne Laser Target Designator System for the first laser-guided bombs (LGBs), the M-117 and the Mark 84. By the late 1960s, the Air Force was using prototype LGBs in the Vietnam War and "Paveway" laser-guidance kits entered production. Before the end of the war, in 1972, the Air Force was using LGBs to effectively knock out targets, particularly bridges, that hitherto had remained largely immune from aerial bombardment. By 1979 a next generation LGB, the GBU-24, entered the Air Force inventory and during the 1980s the GBU-27 and

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[4]   Report, Dr. James F. Aldridge, ASC/HO, "A Historical Overview of the Mission and Organization of the Wright Laboratory, 1917-1993," Nov 1994, pp. 14-15.

[5]   "USAF R&D," p. 89.

[6]   The laser (for light amplification by stimulated emission of radiation) was first demonstrated in 1960 by Theodore H. Maiman of Hughes Research Laboratories. See Article, n.a., "Laser," *Encyclopedia Americana* (Danbury, Connecticut: Grolier), 2000, vol. 16, p. 777.

GBU-28 LGBs were acquired in time for devastating use in the Persian Gulf War.[7]

Beginning in the mid 1960s with the Advanced Development Program (ADP-679A), the Avionics Laboratory also explored electro-optical (EO) guidance technologies. EO technology offered autonomous target lock-on and extreme precision. The AIMPOINT system, demonstrated in the mid 1970s, was a direct result of this research. While it was never fielded, AIMPOINT technology supported the Army's Pershing II ballistic missile's Radar Area Guidance (RADAG) system and the F-111's Radar Correlation Bombing System.[8]

In the mid 1970s, the Avionics Laboratory became the principal technical agent for the Defense Advanced Research Project Agency's (DARPA's) Autonomous Terminal Homing (ATH) program, which sought to develop precision guidance as a means of substituting non-nuclear munitions for missions that hitherto could only be accomplished by nuclear weapons. During Phase I of ATH, the Avionics Laboratory examined sensors and scene signatures measurements, reference preparation techniques, and scene matching algorithms. During Phase II, the laboratory conducted a realistic performance assessment of subsystem technologies that had emerged from Phase I vetting of technical alternatives. As a result of Phase IIA, the Avionics Laboratory recommended a laser radar sensor for achieving precision goals under a larger variety of adverse weather conditions and featured matching algorithms for superior performance in aimpoint determination.[9]

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[7] Background paper, Thomas W. Thompson, AFRL/IFOI, "Laser-Guided Bombs," n.d.

[8] "USAF R&D," p. 90.

[9] "USAF R&D," pp. 90-91.

In 1983, the Air Force directed the consolidation of the Air Force's ATH efforts with several similar efforts to form the Cruise Missile Advanced Guidance (CMAG) program.[10] The CMAG's principal sensor was a carbon dioxide laser radar. The CMAG program concentrated development efforts in five key areas: (1) precision terminal homing, (2) improved midcourse navigation, (3) terrain-following and obstacle avoidance, (4) mobile target identification and submunition cueing for attacking multiple targets, and (5) autonomous strategic bomb damage assessment.[11] In 1987, management of the CMAG program was transferred to Eglin AFB, where the program's focus was shifted to shorter-range tactical weapons applications.[12]

The remodeled CMAG program did not last long, and in 1988, funding was cancelled. Cancellation was due to the appearance of more capable and less expensive guidance technologies, in particular those connected with the global positioning system (GPS) and true all-weather capability.[13] However, technologies developed by the CMAG program still found applications, in particular, the program's laser radar technology. Programs that benefited from CMAG were the Advanced Cruise Missile (ACM), Quiet Knight, and Ballistic Winds.[14]

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[10] Technology program plan, n.a., "Cruise Missile Advanced Guidance (CMAG) Associate Support Activities," n.d; Technology program plan, n.a., "Cruise Missile Advanced Guidance (CMAG) System Developments I and II," n.d.; Background paper, n.a., "Cruise Missile Advanced Guidance (CMAG)," n.d.

[11] History, ASD/HO, "History of the Aeronautical Systems Division, CY 1986, part II: History of the Air Force Wright Aeronautical Laboratories, CY 1984-1986," July 1987, vol. 1, pp. 108-109.

[12] "USAF R&D," p. 92.

[13] The Joint Directed Attack Munition (JDAM) system with inertial navigation and global positioning (GPS) guidance cost less than $25,000 per unit. See "USAF R&D," p. 119.

[14] "USAF R&D," pp. 92-3.

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